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Railway deformation detected by DInSAR over active sinkholes in the Ebro Valley evaporite karst, Spain

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Abstract. Subsidence was measured for the first time on railway tracks in the central sector of Ebro Valley (NE Spain) using DInSAR techniques. This area is affected by evaporite karst and the analyzed railway corridors traverse active sinkholes that produce deformations in these infrastructures. One of the railway tracks affected by slight settlements corresponds to the Madrid-Barcelona high-speed line, a transport infrastructure highly vulnerable to ground deformation processes. Our analysis based on DInSAR measurements and geomorphological surveys indicate that this line show dissolution-induced subsidence and compaction of anthropogenic deposits (infills and embankments). Significant sinkhole-related subsidence was also measured by DInSAR techniques in the Castejón-Zaragoza conventional railway line. This study demonstrates that DInSAR velocity maps, coupled with detailed geomorphological surveys, may help in the identification of the sections in the railway tracks affected by active subsidence.

1 Introduction

The occurrence and activity of sinkholes in carbonate and evaporite karst terrains is one of the main causes of subsidence-related damage and accidents in conventional railways (Guerrero et al., 2008). Deflections in the railway track caused by dissolution-induced settlement can compromise safety on transportation infrastructure (Gourc et al., 1999). The implementation of monitoring and early-warning systems in potentially problematic railway stretches may constitute an effective mitigation measure, mainly aimed at preventing accidents. Differential Synthetic Aperture Radar Interferometry (DInSAR) may be postulated as a useful subsidence monitoring technique for railways. Most of the reported InSAR applications to the monitoring of high-speed railways (HSR) have been developed in China and Taiwan. In these countries, railway and highway infrastructure are experiencing a rapid development and traverse numerous areas affected by ground instability phenomena (Ge et al., 2008, 2009; Shi et al., 2010; Tan et al., 2010; Wu et al., 2010; Zhang et al., 2010; Chen et al., 2012; Hung et al., 2010; Ge et al., 2013). The instability processes that produce most problems in Chinese railways and are the main targets of InSAR analyses are related to groundwater abstraction (Hung et al., 2010; Zhang et al., 2010) and permafrost (Chen et al., 2013; Shi et al., 2014). In a railway built upon permafrost, Shi et al. (2014) documented temporal variations of deformation in relation with rainfall and air temperature and measured higher strain in topographically lower areas, where water accumulation increases the impact of thawing and freezing. On the other hand, the activity of sinkholes has been monitored using DInSAR in different geological settings of Germany (Schäffer, 2009), Israel (Baer at el., 2002; Abelson et al., 2003; Nof et al., 2013), Italy (Ferretti et al., 2000, 2004), Jordan (Closson et al., 2005, 2010), Spain (Castañeda et al., 2009, 2011; Gutiérrez et al., 2011; Galve et al., 2015) and USA (Al-Fares, 2005; Paine et al., 2012).

Here, we present DInSAR displacement profiles that reveal previously undetected active subsidence on sections of different railways in the surroundings of Zaragoza city, Ebro Valley evaporite karst, NE Spain (Figure 01). The Cenozoic bedrock in the analysed area of the Ebro Valley consist of subhorizontally lying halite- and glauberite bearing evaporites of the Zaragoza Formation (Salvany et al., 2007)(Figure 02). Subsurface dissolution results in the development of numerous sinkholes affecting both the evaporitc bedrock and the alluvial cover (Galve et al., 2009; Pueyo-Anchuela et al., 2015, and references therein). Active subsidence associated with these sinkholes produce costly damage to human structures (e.g., Gutiérrez et al., 2009, 2015). The dissolution-induced ground deformation can be studied quantitatively using InSAR techniques as illustrated by previous works (cf., Castañeda et al., 2009, 2011; Gutiérrez et al., 2011; Galve et al., 2015).

We have analyzed two railway stretches. One of them includes two parallel railways, a conventional one and the Madrid-Barcelona high-speed line. Here, 1850 m and 1900 m long sections are built on embankments and in excavated trenches, respectively. The latter are flanked by cuttings that expose subsidence structures. The other strecht with active subsidence includes a 4000 m long section of the conventional Castejón-Zaragoza railway (Figure 01). Both railway corridors traverse large sinkholes previously documented in geomorphological maps (Simón et al., 1998, 2003; Galve et al., 2009). On 1 March 2003, a collapse sinkhole 5 m across formed beneath the high-speed railway a few months before its inauguration (Guerrero et al., 2008). We observed obvious deformation in a poorly maintained subsidiary railroad of the Castejón-Zaragoza line, coinciding with the location of an active sinkhole mapped on the basis of geomorphic criteria (Figure 03). Moreover, on 11 September 1991, a collapse sinkhole caused the derailment of a freight train in the conventional Madrid-Barcelona railway downstream of Zaragoza city (at Km, 360.7; Gutiérrez et al., 2007)(Figure 02). In this work we integrate DInSAR deformation data with different subsidence evidence (geomorphic, deformed sediments, damaged human structures). The convergence of the different lines of evidence is used to support the utility of DInSAR for monitoring railways affected by dissolution-induced subsidence.

2 SAR data and processing methods

Archived data from two orbital SAR missions have been used to produce the InSAR deformation maps analysed in this work. One of the datasets includes C-band data of 29 ENVISAT ASAR images acquired at 10.00 p.m. on ascending orbits from 2 May 2003 to 17 September 2010 (track 58, frame 829). The other dataset comprises L-band data of 13 ALOS PALSAR images acquired at 10.30 p.m. on ascending mode, HH polarisation, and covering a period from 12 February 2007 to 7 April 2010 (track 665, frame 820).

The SAR images were processed using the Stable Point Network (SPN) technique (Crosetto et al., 2008)). Preprocessing was carried out using the DIAPASON interferometric algorithm (Massonet and Feigl, 1998). This algorithm incorporates the persistent scatterers and the distributed scatterers approaches based on full resolution and medium resolution data, respectively. The topographic component of the interferometric phase was removed using the Spanish photogrammetric elevation model 'GISOleícola' with a spatial resolution of 20 m.

The ENVISAT-ASAR-derived displacement rate map was produced at full resolution from a total of 61 interferograms. The persistent scatterers (PS) were selected establishing a coherence threshold of 0.46 on the basis of the SAR amplitude selection criterion. The average LOS displacement rate and the LOS displacement time series of each PS were derived from the Single Look Complex (SLC) ASAR images. Displacement rate values >2 mm/yr were considered as non-stable points as it is usually defined for ENVISAT C-band data (Meisina et al., 2008; Bianchini et al., 2013). The ALOS-PALSAR-derived displacement rate map was produced at a ground resolution of about 25 × 25 m and establishing a coherence threshold of 0.40. In this case, displacement rates >4 mm/yr were considered as indicative of surface deformation. This threshold is consistent with values used by other authors (Sandwell et al., 2007; Bianchini et al., 2013)

3 Railway deformation detected by DInSAR and interpretation

Railways behaved as good reflection features for ALOS and ENVISAT sensors, providing a relatively high density of measurement points, especially in the ALOS-derived map. Two profiles of LOS displacement rates have been constructed along the railway corridors using the InSAR maps (Figure 04). We analysed ALOS and ENVISAT data in each profile and selected the best results to be presented in this work; ALOS measurements in the Castejón-Zaragoza railway line and ENVISAT PS points in the Madrid-Zaragoza profile (Figure 04).

The displacement rates measured in the SW and NE portions of the analyzed Madrid-Zaragoza railway section, as high as -6.6 mm/yr (negative values indicate subsidence), may be related to compaction of the embankments, as suggests the direct correlation between subsidence rates and embankment height (Figure 04, Profile 1). LOS displacement rates indicate rapid settlement (>4 mm/yr) in the NE sector of the analysed stretch, coinciding with the location of a buried depression of unknown origin, filled a few decades ago and identified with aerial photographs. Here, subsidence is most probably related to compaction of anthropogenic deposits, which may exceed 10 m including the embankment. However, further investigations would be required to rule out the potential contribution of dissolution-induced subsidence (e.g. trenching, geophysics, vertical extensometers).

The negative LOS displacement values measured in the sector where the right-of-way of the railway has been excavated in Quaternary alluvium can be attributed to dissolution-induced subsidence. Between 1500 m and 2700 m in profile 1, there is a significant number of points with LOS displacement rates below -2 mm/yr. In this sector, the railways run across subdued sinkholes recognized in old aerial photographs and expressed in the cuttings as deformed Quaternary alluvium (Simón et al., 1998, 2003; Galve et al., 2009). The sinkhole cluster comprises a large diffuse-edged depression and several smaller subcircular sinkholes (Galve et al., 2009)(Figure 05). In addition to the DInSAR deformation data, several lines of evidence consistently indicate active subsidence in some sectors of the sinkhole cluster: enclosed depressions, severe cracking on buildings, conspicuous sags and wide fissures on roads and small collapse sinkholes, including the 2003 event. An excavation carried out at the SW edge of the large depression for the foundation of a bridge exposed tilted Quaternary deposits dipping toward the depression center (Figure 05). Two sedimentary packages were differentiated. The lower one corresponds to pre-sinkhole terrace gravel deposits with an apparent NE dip of 14-17º. The upper one is a natural sinkhole fill deposits that pinches out towards the SW (sinkhole edge). The dip of these sediments progressively attenuates upwards (cumulative wedgeout) suggesting synsedimentary subsidence.

The high density of measurement points derived from the ALOS data along the Castejón-Zaragoza railway provides valuable information on the activity of three previously inventoried sinkholes traversed by the infrastructure. A clear subsidence zone, with negative LOS displacement rates as high as -9.7 mm/yr, coincides with a sinkhole about 300 m across previously classified as active (Figure 03 and Figure 04, Profile 2). Here, ground motion values show a consistent pattern with increasing subsidence rates towards the center of the sinkhole (Figure 03). The LOS displacement values measured in the other two sinkholes, previously described as inactive (Galve et al., 2009), suggest ground stability or very slow subsidence (< 2 mm/yr).

4 Discussion

The presented data illustrates that DInSAR offers a promising potential for monitoring railways affected by sinkhole activity and dissolution-induced subsidence. This postulate is supported by two relevant aspects of our investigation: (1) There is a good spatial correlation between the deformation values measured by DInSAR and unambiguous field evidence of active subsidence associated with sinkholes. (2) We obtained good results using InSAR data derived from a regional investigation (see Galve et al., 2015). Detailed analyses focused on railway tracks or on specific sections of the infrastructure should provide higher density and more accurate deformation data than in the profiles presented in this paper.

Railways are linear features commonly laying on relatively flat surfaces that behave as adequate reflectors for the spaceborne SAR systems, providing spatially dense and temporarily stable coherent scatterers (Hanssen et al., 2009; Shi et al., 2014). Chen et al. (2012) illustrate the strong backscattering of railways in ALOS PALSAR and ENVISAT ASAR amplitude images, compared with the surrounding features. The density of natural reflection points depends on the land cover, the number of images used in the InSAR analysis, the adopted processing parameters and algorithm type, the selected coherence threshold, and the spatial resolution of radar imagery (Wasowsky et al., 2014). In our case, ENVISAT displacement points cover a larger area in the Madrid-Zaragoza profiles (NW-SE orientation) than the ALOS displacement data. On the contrary, ALOS data provided the best distribution of measured points along the Castejón-Zaragoza stretch (NE-SW orientation). Apparently, this difference could be attributed to the relative orientation of the railway tracks with respect to the flight path of sensors. However, both the ENVISAT and ALOS data correspond to ascending paths and, consequently, the differences observed between the two DInSAR displacement rate maps cannot be related to the course of the satellites. Ge et al. (2008) and Shi et al. (2010) have obtained deformation sequences covering long time spans analyzing PSs along railways. Shi et al. (2010) measured numerous minor and locally distributed displacements that were not detected by leveling. Chen et al. (2012) obtained a higher density of PSs with ALOS PALSAR data than with ENVISAT ASAR data. This was probably due to the longer wavelength of the former and the higher critical baseline applied to generate the ALOS interferograms of SBAS method (Lanari et al, 2004). This resulted in higher coherence, especially in zones with high deformation gradients and in manmade features such as the railway embankment. This author inferred that the difference in the distribution of PSs derived from L-band and C-band data are controlled by their different scattering mechanism. In PALSAR results, the railway embankment was more easily detected because of its resolution (10 m). Man-made linear features were dominated by the dihedral scattering and resulted in high density of PS points in PALSAR results. For ENVISAT data, despite the strong backscattering of the railway, motion was not detected using PS method probably due to the noise caused by the scattering mechanism of instable land surfaces.

5 Conclusions and final considerations

DInSAR techniques allowed in the detection of previously unknown settlement in several stretches of two major railway lines of NE Spain. This area in the outskirts of Zaragoza city is severely affected by evaporite karst subsidence. This deformation was detected thanks to medium-resolution surface velocity maps generated through the analysis of archived data of the ENVISAT and ALOS SAR missions. The results show that DInSAR methods allow identifying and monitoring deformation on railways that may compromise both serviceability and safety.

DInSAR velocity maps coupled with detailed geomorphological maps may help in the identification and characterization of the railway stretches affected by active deformation that may require site-specific monitoring. These stretches may be controlled by using real-time advanced ground-based monitoring techniques such as motorized total station systems that measure prisms attached directly to the structure, time-domain reflectometry (TDR) coaxial cable sensors (cf., O'Connor et al., 2004) or GB-InSAR (cf., Intrieri et al., 2015). DInSAR also could be an alternative to these expensive techniques where catastrophic collapse can be ruled out and the ground deformation does not show dangerous subsidence rates (according to the admissible deformation of the railway track). Site-specific investigations combining more adequate and higher resolution SAR data with ground references (e.g. corner reflectors, GPS benchmarks) may provide a very precise monitoring system. PS detection in linear infrastructures is improving substantially by using high resolution data (e.g. CosmoSkyMed, TerraSAR-X) (Ge et al., 2013; Nutricato et al., 2013; Yu et al., 2013; Luo et al., 2014). High-resolution imagery can provide a point density ten times higher than medium-resolution data (Bovenga et al., 2012). Yu et al. (2013) found dense PSs in highways and railways using high resolution TerraSAR-X data due to the presence of numerous stable objects distributed along the infrastructures, such as lamps, stones or fences. Future studies in our study area should focus on the deformation monitoring using TerraSAR-X, COSMO-SkyMed data coupled with other ground-based measurements.

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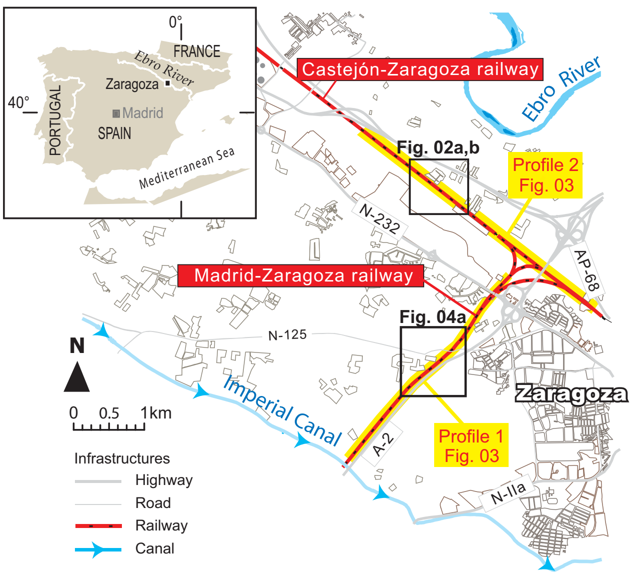

Figure 01. Geographic location of the studied railway sections.

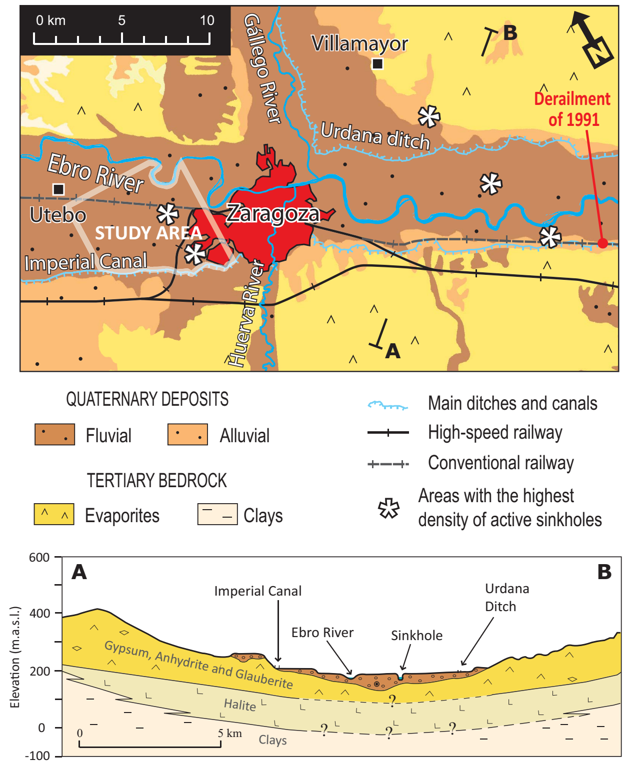

Figure 02. Geological map of the surroundings of Zaragoza city and geological cross-section of the central sector of the Ebro Valley. From the geological point of view, the railway tracks crosses the central sector of the Ebro Cenozoic Basin and is underlain by sub-horizontally lying evaporites of the Oligo-Miocene Zaragoza Gypsum Formation (Quirantes, 1978). This formation is composed of gypsum, anhydrite, glauberite and halite units (Salvany et al., 2007). Sinkholes are caused by subsurface dissolution and the consequent deformation and/or internal erosion of the overlying sediments. Detailed descriptions on the dissolution and subsidence processes in the study area can be found in Gutiérrez et al. (2008), Galve et al. (2009) and Acero et al. (2015).

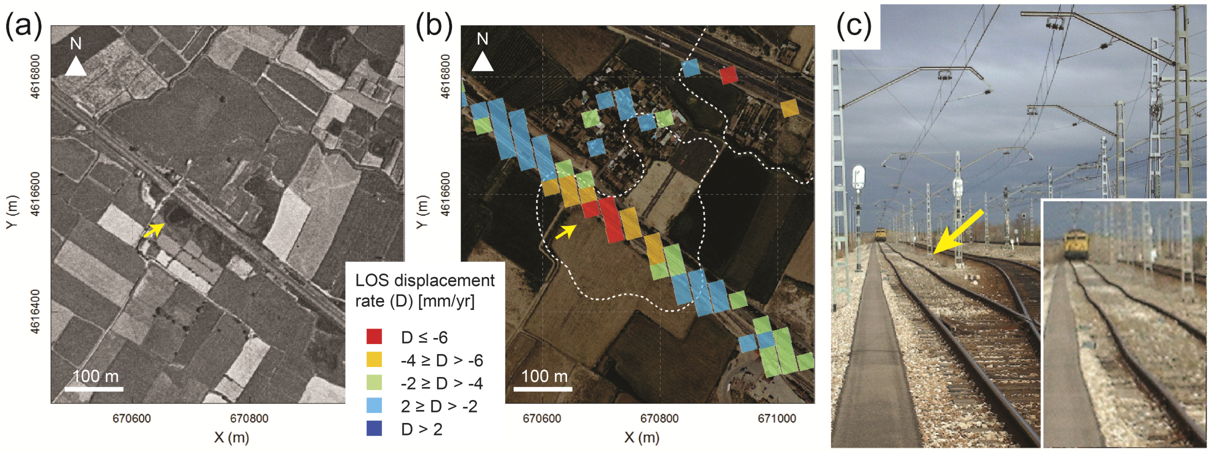

Figure 03. Section of the Castejón-Zaragoza railway built on a buried sinkhole and affected by active karst subsidence. (a) Aerial photograph taken in 1956. Arrow points to a ponded sector within the large subsidence depression. (b) Orthoimage from 2009 with ALOS-derived displacement rates on PSs. Dotted white line defines the boundaries of known active sinkholes (c) Photographs of the location indicated with arrows in (a) and (b), showing obvious deformation in the railways.

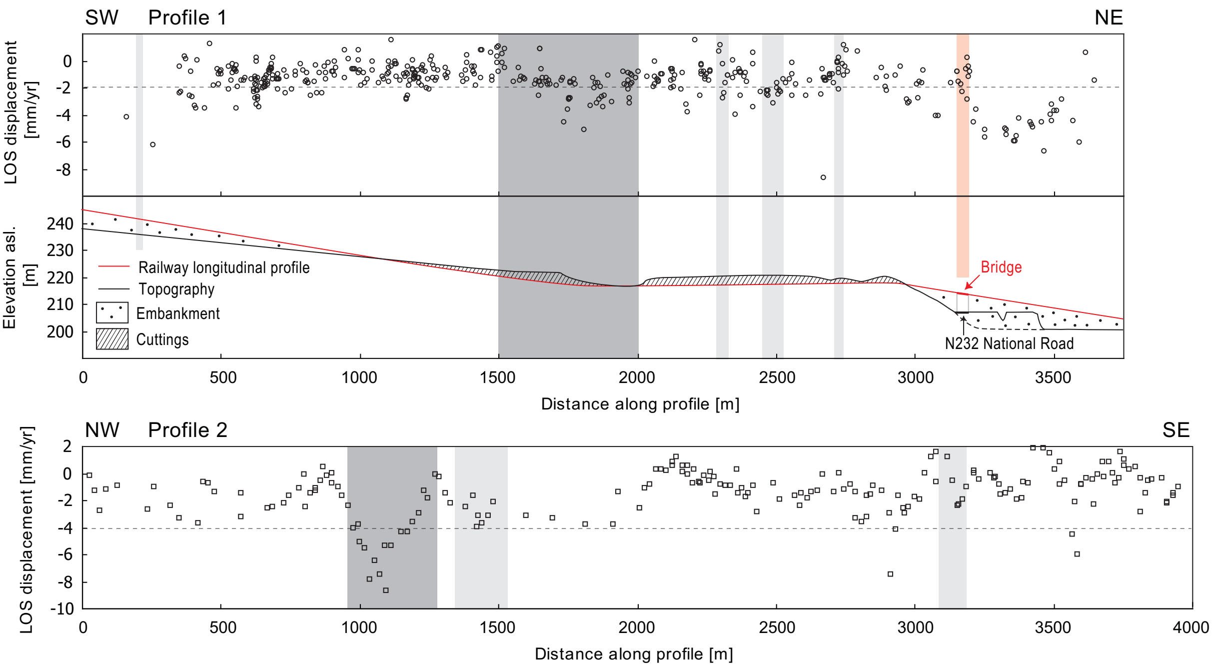

Figure 04. Profiles with DInSAR-derived LOS deformation data obtained along the analyzed railway sections. Data from the Madrid-Barcelona railway corridor is represented alongside a topographic profile showing the stretches built on embankment and excavated trenches. Dark grey and light grey zones indicate sections built on sinkholes classified as active and inactive, respectively. See location of profiles in Figure 01.

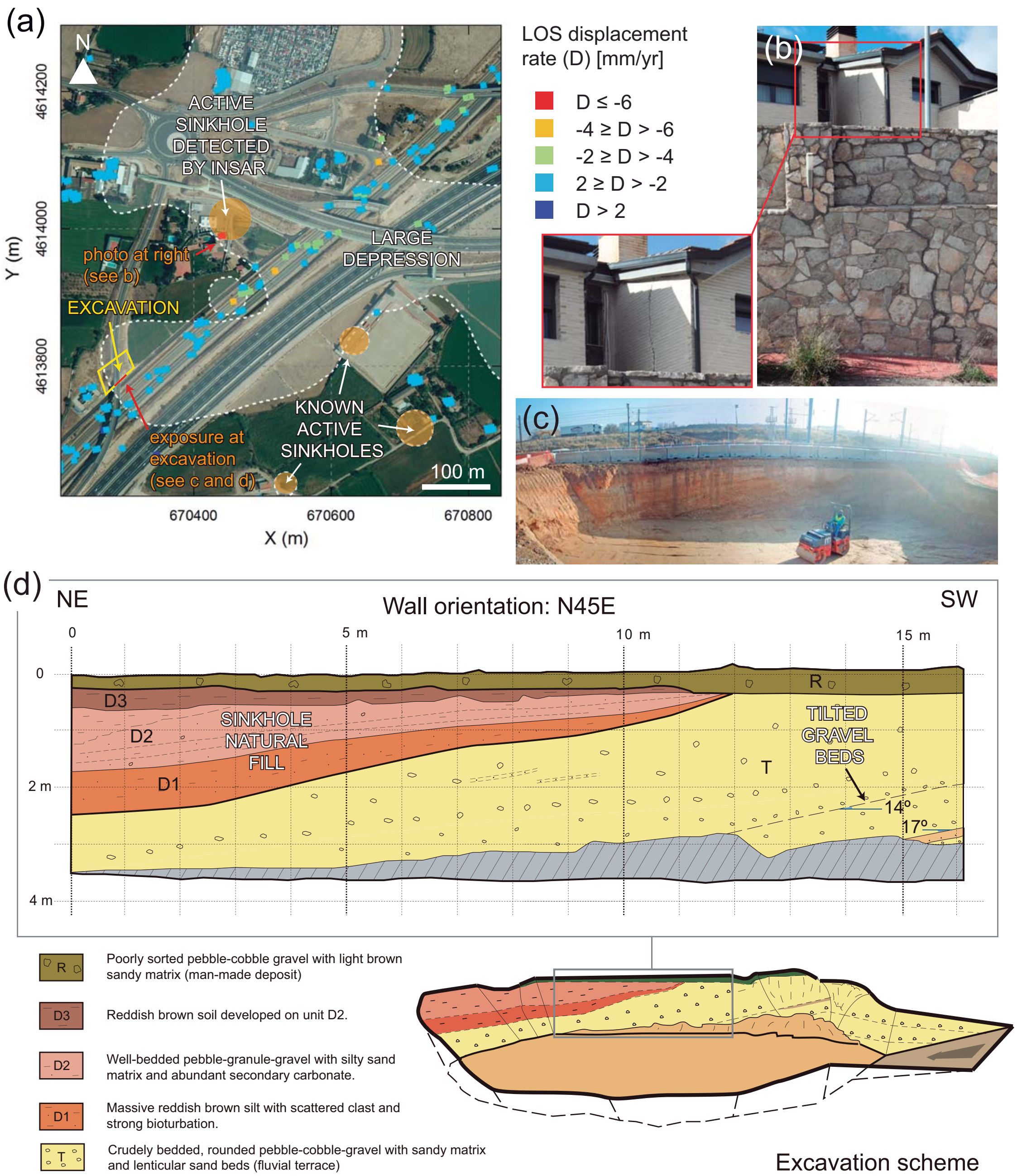

Figure 05. Evidence of karst subsidence associated with the track of the Madrid-Zaragoza high-speed railway. (a) Orthoimage of 2009 with ENVISAT DInSAR PS data indicating the main sinkholes and large karst depressions. (b) Cracks on a house where ENVISAT DInSAR map indicate subsidence. (c) General view of the excavation indicated in (a). (d) Log and scheme of the walls of the excavation. Note the wedging-out of the sinkhole fill and the tilted terrace gravel beds.

Table 01. Main characteristics of the SAR datasets and DInSAR deformation profiles

	ENVISAT	ALOS
SAR acquisition		
Band / Polarisation	C / VV	L / HH
Wavelength [cm]	5.6	23.6
Incidence angle	23	38.7
Revisiting period [days]	35	46
Orbital track / Frame	58 / 829	665 / 820
Acquisition geometry	Ascending	Ascending
Pixel size [m] radar geometry	4 x 10	8 x 4
Data set period	05/2003–09/2010 (7.38 yrs)	02/2007–04/2010 (3.15 yrs)
Temporal span between two acquisitions [days]		
Mean	96	96
Maximum	700	414
Minimum	5	46
SAR processing		
Number of SAR images	29	13
Number of interferograms	61	78
Maximum spatial baseline [m]	138	393
Maximum temporal baseline [days]	1050	1150
DEM (pixel size)	GIS Oleícola (20 m)	GIS Oleícola (20 m)
Coherence threshold	0.46	0.4
DInSAR deformation profiles		
Railway line	Madrid-Barcelona	Castejón-Zaragoza
Length [km]	3.75	4
Width [m]	50	70
No. of measurement points	436	198
Type of point	Persistent scatterer	Pixel (25 m)
Density of measurement points [points/km]	116.3	49.5
LOS displacement rate [mm/yr]		
Mean	-1.4	-2.4
Maximum value (uplift)	2.1	1
Minimum value (subsidence)	-8.6	-9.7
Standard deviation	1.3	1.8
Cumulative LOS displacement [mm]		
Mean	-11.1	-7
Maximum value (uplift)	12	3.9
Minimum value (subsidence)	-57.6	-28.9
Standard deviation	9.5	5.2