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Anthropogenic subsidence along railway and road infrastructures in Northern Italy highlighted by Cosmo-SkyMed satellite data

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Abstract. We use X-band Cosmo-SkyMed InSAR data to highlight several subsidence phenomena resting on some railway and road infrastructures in Lombardia region, Northern Italy, mainly induced by anthropogenic activities. We show eight case studies, namely "Como," Erba, Oggiono, Valmadrera, Olginate, Verduggio, Melzo, and San Giuliano M., where we detect local subsidence effects affecting several railway and highway lines with deformation rates of about 5 mm/year. The geological features of this part of Italy and the large presence of industrial areas in the surrounding of Milano, Lecco, and Como cities lead to such phenomena. The stability and security of the nested road and railway network could be affected by these surface deformation fields. To guarantee the safety of people, continuous maintenance of the condition of railways and roads together with the monitoring of the conditions of the lands on which they rest on should be done. [DOI: 10.1117/1.JRS.13.024515]

Keywords: synthetic aperture radar interferometry; Northern Italy; subsidence; railway and road infrastructure; anthrophogenic-induced effects.

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1 Introduction

Since the beginning of the 90s, synthetic aperture radar interferometry (InSAR) data have been used for supporting the analysis of several natural phenomena, such as earthquakes, volcanoes, landslides, and so on.[1–3] Indeed, based on the phase of the backscattered signals, the InSAR data are able to constrain along the satellite line-of-sight (LoS) any crustal deformation allowing to have real information about a ground displacement field. The increasing number of space missions together with the rapid development of SAR sensors and algorithms of data processing, such as persistent scatterers (PS),[4] small baseline subsets (SBAS),[5] interferometric point target analysis (IPTA)[6] and SqueeSAR,[7] made it possible to improve quality and resolution of the acquired images and then the InSAR products providing deformation measurements in the order of millimeters.[8] This allowed to reduce the scale of the observed phenomena giving the opportunity to exploit InSAR data for studying urban areas,[9,10] civil infrastructures, and even single buildings.[11] Nowadays, InSAR products are applied in the analysis of deformations occurring on dams,[12,13] bridges,[14] railways,[15] or roads,[16] which are often affected by thermal effects, inducing a periodic quasi-sinusoidal seasonal-dependent deformation.[17] However, sometimes they are subject to greater stress fields produced by other phenomena, such as natural- or anthropogenic-induced subsidence that can be dangerous for the stability of the structure itself even causing damages and collapses.[18,19]

In this work, we exploited X-band Cosmo-SkyMed (CSK) InSAR data to detect some anthropogenic-induced local subsidence phenomena resting on several railways and highways in Lombardia region, Northern Italy, in the proximity of Milano city and between Lecco and Como cities. This sector of Italy has already been investigated in several studies, revealing some subsidence phenomena in the surrounding of Po Plain.[20–23]

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Lombardia is one of the most industrialized areas of Italy with the large presence of many metallurgical plants and crude oil refineries together with active and/or ceased quarries, several industries in the mechanical, chemical and textile sectors, reclaimed sites, waste treatment sites, and landfills. This intense anthropogenic-industrial activity produces several subsidence effects due to excessive groundwater exploitation,[24] extraction of hydrocarbons[25] and hydrogeological reclamations[26] especially in proximity of lakes such as Lake Como, Lake Annone, and Lake Pusiano. At the same time, Lombardia has a very widespread railway and road network with many intraregional connections to Milano or toward Switzerland or neighboring Veneto and Piemonte regions. Unfortunately, on January 2018 a train accident occurred near the Pioltello station, eastern Milano, which caused three casualties and more than 40 injured. In addition, some criticalities have been observed also on the road infrastructure as, for example, the overpass collapsing close to Annone Brianza town (Lecco) on October 2016.

Every day, more than 700,000 commuters move along the entire region then, in order to guarantee the safety of the people, continuous maintenance of the condition of railways and roads together with the monitoring of the conditions of the lands on which they rest on is needed.

2 Geological Settings

The study area is located in the western sector of the Po Plain, a fluvial basin elongated in an east–west direction between the mountain ranges of the Alps and the Apennines. The Po Plain foredeep is characterized by the convergence of two chains beneath the Po River floodplain: the western southern Alps and the northern Apennines.[27,28] The western southern Alps are related to the subduction of Europe underneath the Adriatic plate, whereas the northern Apennines are generated along the "westward" subduction of the Adriatic lithosphere below the Tyrrhenian basin. Several authors described the regional geological setting and the Quaternary evolution of the area.[29–31] The study area is characterized by three different sectors represented by Mesozoic carbonatic reliefs, Oligo-Miocene conglomerates of the Southern-Alpine molasses, and the Como Quaternary basin. The Mesozoic carbonatic sequence is constituted by well-bedded Liassic siliceous limestones; molasse sediments are constituted by coarse polygenic conglomerates and sandstones belonging to the Lombardian Gonfolite Group ("Como Fm.," Upper Oligocene).[32] The study area was affected during the Quaternary by glacial periods, which shaped the landscape morphology with erosional and depositional glaciers activity. Several glacial expansions involved the Central Alps starting from the Middle Pleistocene and generating ice tongues up to 2 km thick, in the piedmont belt and the Northern Po Plain.[33] During the last glacial maximum, 22 to 20 kyr BP,[34] frontal moraines expanded south of Como; in the subsequent early late glacial retreat, a lake formed where glacier deposits, constituted by clay and silt containing clasts and pebbles of varying lithology, sedimented.[35] The progressive lake level lowering developed a lacustrine–palustrine environment in the Como sedimentary basin during the Dryas II–Allerød. During the Holocene, the shallow water basin occupying the Como plain was progressively filled up by the alluvial deposits of the Cosia Stream.[36] The anthropogenic activity produced fires and deforestation increasing the sediment load of the local streams and consequently their depositional capacity. An increase of the thickness of the alluvial sand and gravel deposits took place during the last 3.5 kyr, larger than that deposited during the previous 10 kyr; slope and fan deposits contributed to the infilling of the basin.

3 InSAR Data

The satellite data used in this work consist of two datasets of X-band SAR data acquired in Stripmap mode by the CSK missions of the Italian Space Agency (ASI) from 2014 to 2018. Because of the small wavelength of 3.1 cm, the X-band data allow retrieving high-resolution images (∼3 m) preserving details useful in the study of civil infrastructures. The first dataset, namely in the following "Como–Lecco dataset," consists of 45 single-look complex CSK images acquired along descending orbit from January 2014 to November 2016 and covering the area surrounding Lake Como. On the other hand, the second dataset, hereinafter "Milano dataset," is centered on Milano city, i.e., more southern, and consists of 21 SLC CSK images along ascending orbit spanning from August 2015 to January 2018. Both datasets were multilooked by factors of 5×5 retrieving a pixel posting of about 10 m along both range and azimuth direction. The InSAR processing was performed by multibaseline IPTA approach developed in the framework of GAMMA software.[6] We retrieved a redundant interferogram network for both datasets by setting the threshold of the maximum perpendicular and temporal baseline to 500 m and 600 days for the Como–Lecco dataset and to 1000 m and 1000 days for the Milano dataset. Such different choices, returning, respectively, 319 and 175 interferograms for Como–Lecco and Milano dataset, have been due to the different number of SAR images. In order to remove the topography from the interferometric phase, we used the 30-m digital elevation model provided by the Shuttle Radar Topography Mission (SRTM), oversampled by a factor of 3 to obtain approximately the same size of the SAR images. Goldstein filtering[37] was also applied while the phase unwrapping step was performed by the minimum cost flow (MCF) algorithm.[38]

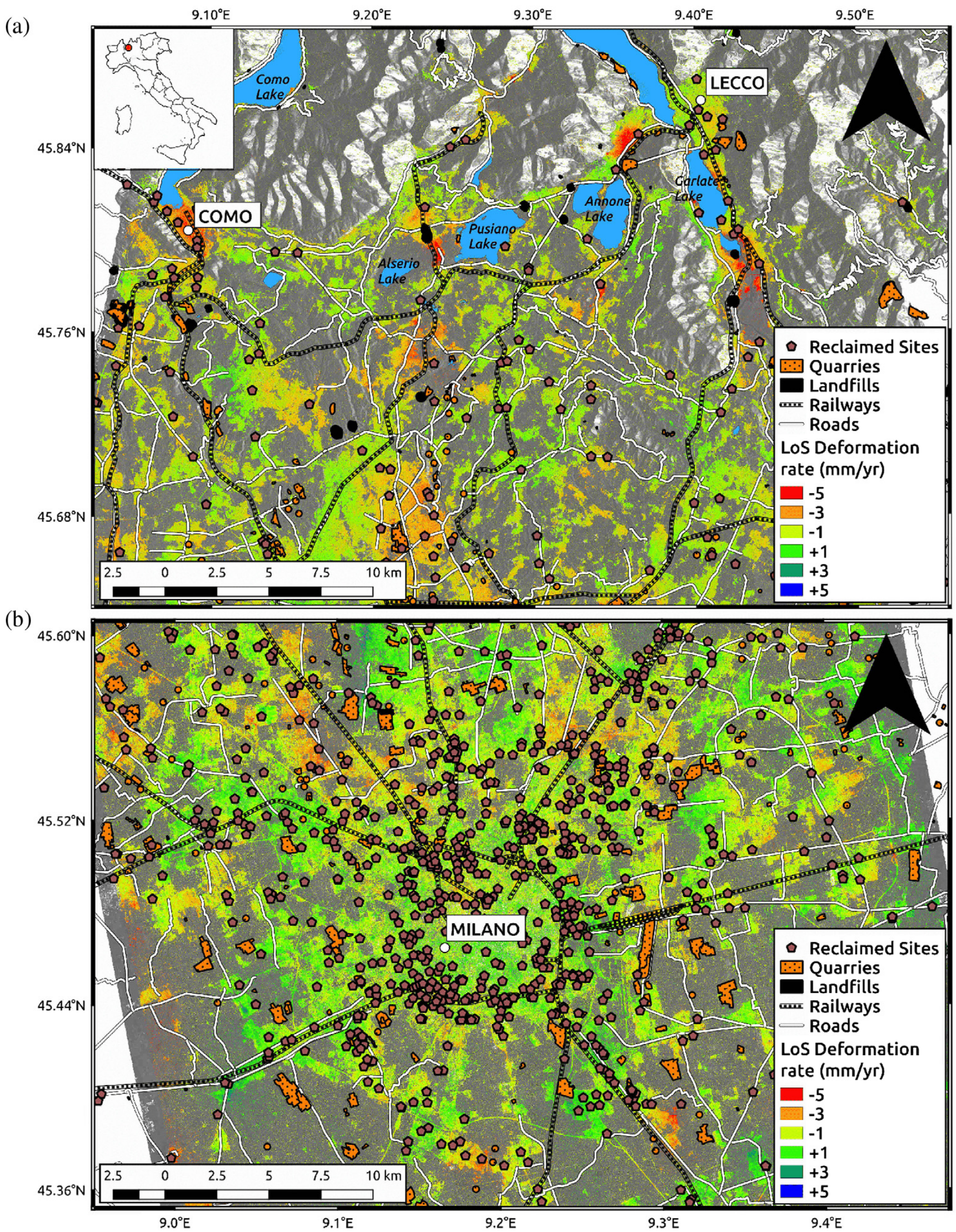

Fig. 1 InSAR deformation velocity maps retrieved by the X-band CSK data. (a) The Como–Lecco dataset and (b) the Milano dataset.

4 Results

The outcomes of the CSK InSAR analysis are shown in Figs. 1 and 2. Deformation rate and time series were estimated along the satellite LoS. Because of the satellite geometry of view, deformation fields induced by subsidence phenomena are well constrained being mainly characterized by vertical displacements.

As clearly observable both in the overview of Fig. 1 and in the focus of Fig. 2, several localized subsidence effects resting on railway and road infrastructures are ongoing in Lombardia region. In particular, in the upper CSK frame, we identified six areas affected by subsidence,

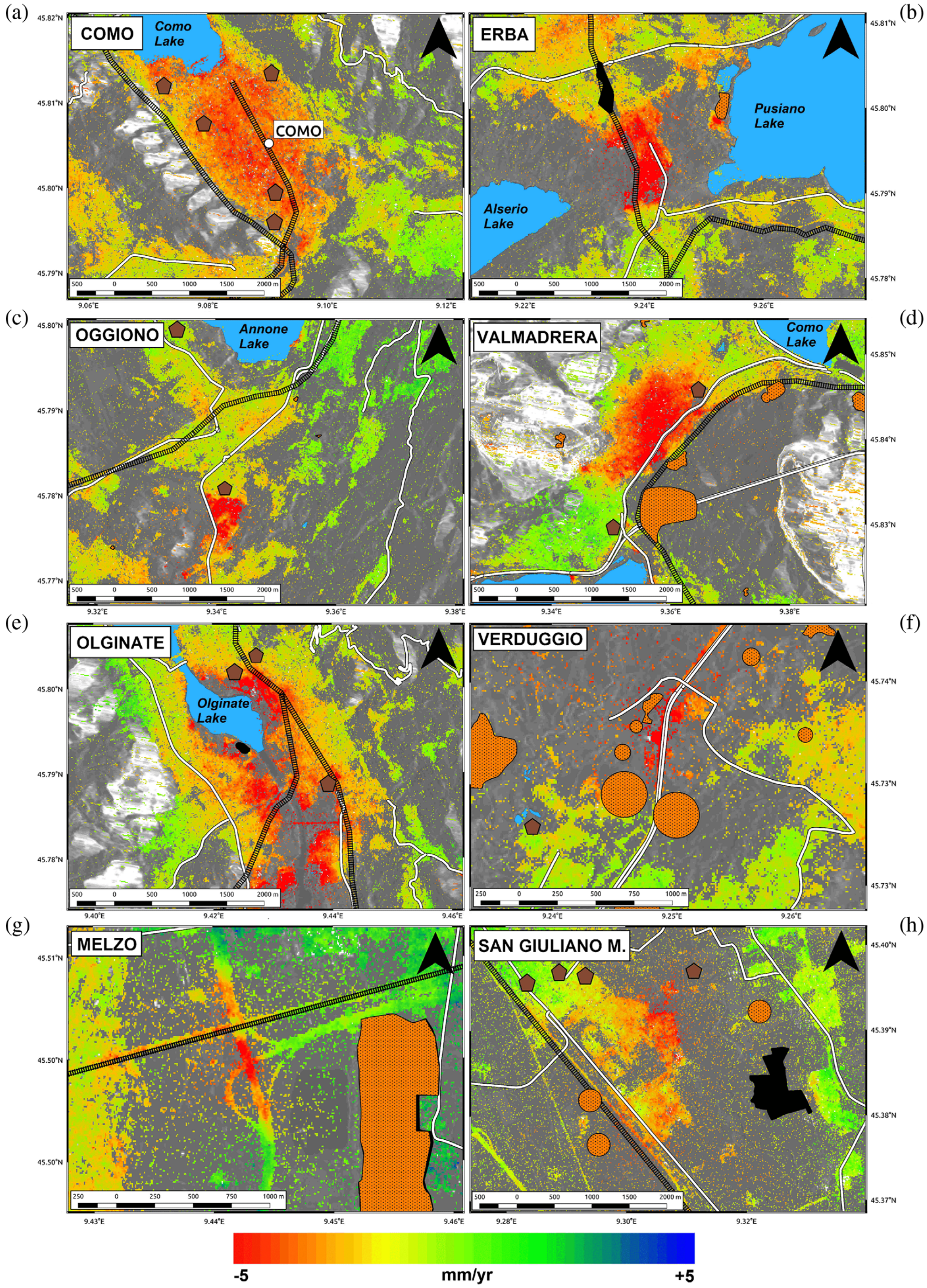

Fig. 2 Focus on the areas affected by subsidence. (a) Como, (b) "Erba," (c) "Oggiono," (d) "Valmadrera," (e) "Olginate," (f) "Verduggio," (g) "Melzo," and (h) "San Giuliano M."

with deformation rates peaking at about 6 to 7 mm/year. They are mainly located in or near several industrial areas along the Como and Lecco provinces and in proximity of lakes, where the presence of soft sediments can lead and facilitate the subsidence process. This is the case of the subsidence phenomena detected in: (1) Como city, in the proximity of the eastern termination of Lake Como, hereinafter Como; (2) the industrial area south of Erba (CO) town, between Lake Pusiano and Lake Alserio, hereinafter Erba; (3) the industrial area south of Oggiono (LC) town and Lake Annone, hereinafter Oggiono; (4) the industrial area of Valmadrera (LC) town, between Lake Annone and the western termination of Lake Como, hereinafter Valmadrera; and (5) several industrial areas along the shores of Lake Garlate and Lake Olginate, hereinafter Olginate. Instead, the last subsidence phenomenon detected in the upper frame is located further south, in the Monza-Brianza province, along the SS36 highway, close the Veduggio con Colzano (MB) town, hereinafter Verduggio. On the other hand, in the second CSK frame, we observed two subsiding areas not so far from Milano city and with subsidence values slightly lower, peaking at about 5 mm/year. The first one is located along the A58 highway, east of Milano city, and close to Melzo (MI) town, hereinafter Melzo, whereas the second one surrounds the industrial areas of San Giuliano Milanese (MI), south of Milano city, hereinafter San Giuliano M. Avoiding the seasonal fluctuations, the time series show an almost linear trend for all the observed phenomena except for the Erba case study, where we observed an increase of the subsidence rate starting from May 2015. Melzo and San Giuliano M. case studies are characterized by a worse temporal sampling due to the fewer number of images available for the Milano dataset (Fig. 3). Such results are consistent with the slow and persistent in time, subsidence produced by the combination of several anthropogenic-induced factors as soil compaction, water pumping for industrial activities, and so on.

We explored several GNSS and leveling network based on previous studies and regional online services[22,39] to validate our results. Unfortunately, the observed subsidence phenomena are too local and only three GPS sites cover the InSAR frames. They are located in Como, where

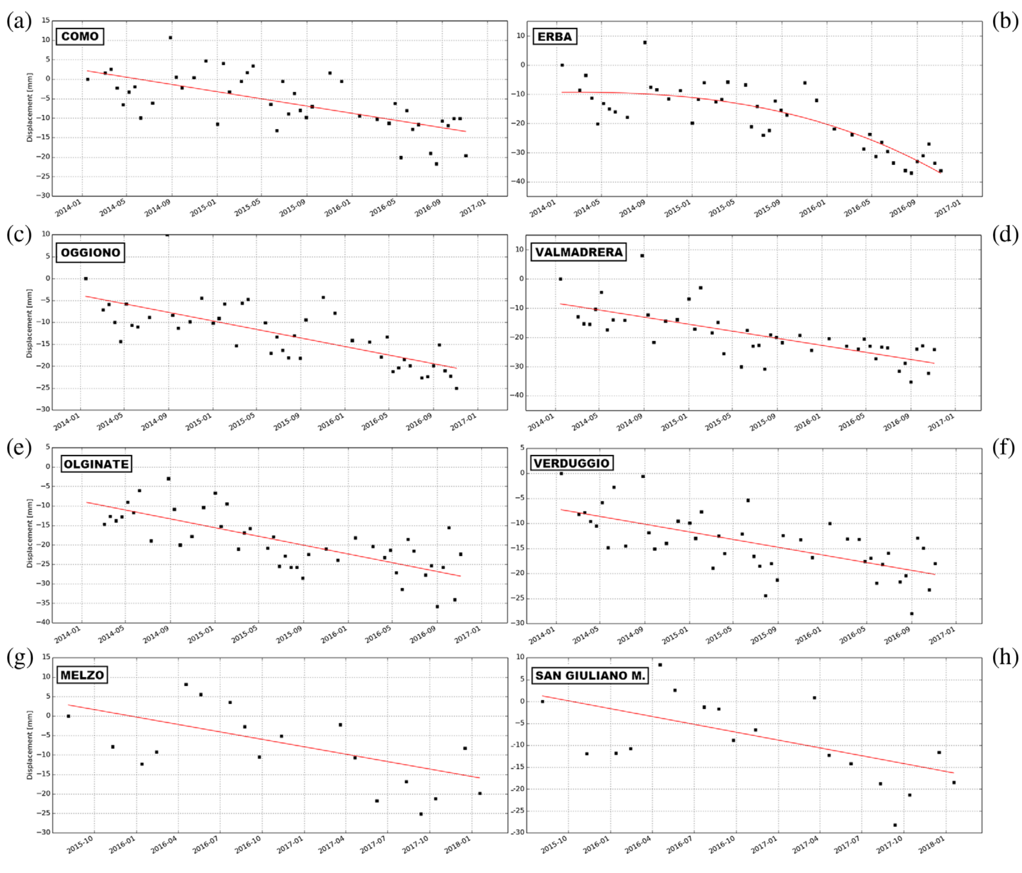

Fig. 3 Time series estimated along the areas highlighted in Fig. 2. (a) Como, (b) Erba, (c) Oggiono, (d) Valmadrera, (e) Olginate, (f) Verduggio, (g) Melzo, and (h) San Giuliano M.

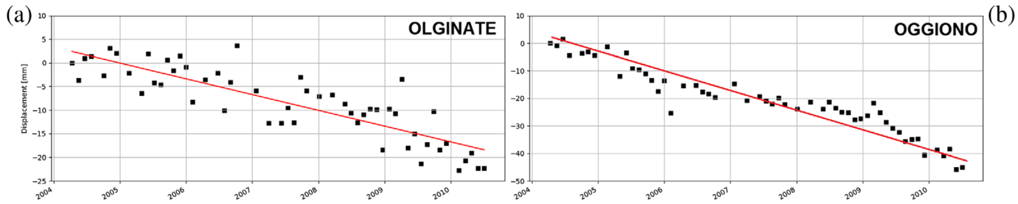

Fig. 4 (a) and (b) Point series retrieved by the PST project providing a cross-validation of the results.

the subsidence is already well known in the literature[36] and in Lecco and Milano cities, where no deformation is observed. However, in order to carry out a sort of cross-validation, we exploited the ENVISAT InSAR data provided in the framework of the Italian project Piano Straordinario di Telerilevamento (PST).[40] Such data are acquired in the time interval ranging from 2003 to 2010, i.e., several years before our CSK dataset but most of the deformation we observed show an almost linear behavior and we indeed found a general good agreement. In addition, it demonstrates how some of the detected phenomena are persistent over time (Fig. 4).

5 Discussion

The detected subsidence phenomena directly or indirectly involve several anthropogenic activities largely present between Como, Lecco, Monza-Brianza, and Milano provinces.

In the case of Erba, Oggiono, Olginate, and San Giuliano M., such phenomena are strictly connected to the soil compaction effects induced by the relatively recent industrial development in the peripheral areas as clearly observable in Fig. 5. Indeed, in these areas, there are nowadays many metallurgy industries, industries for the production of rolled steel strips, fastening systems, protective treatments for small mechanical parts and metal components, packaging industries, metallic carpentry industries, and commercial areas. In addition, in the immediate surrounding of the subsiding areas, many reclaimed sites, quarries, and landfills are present.

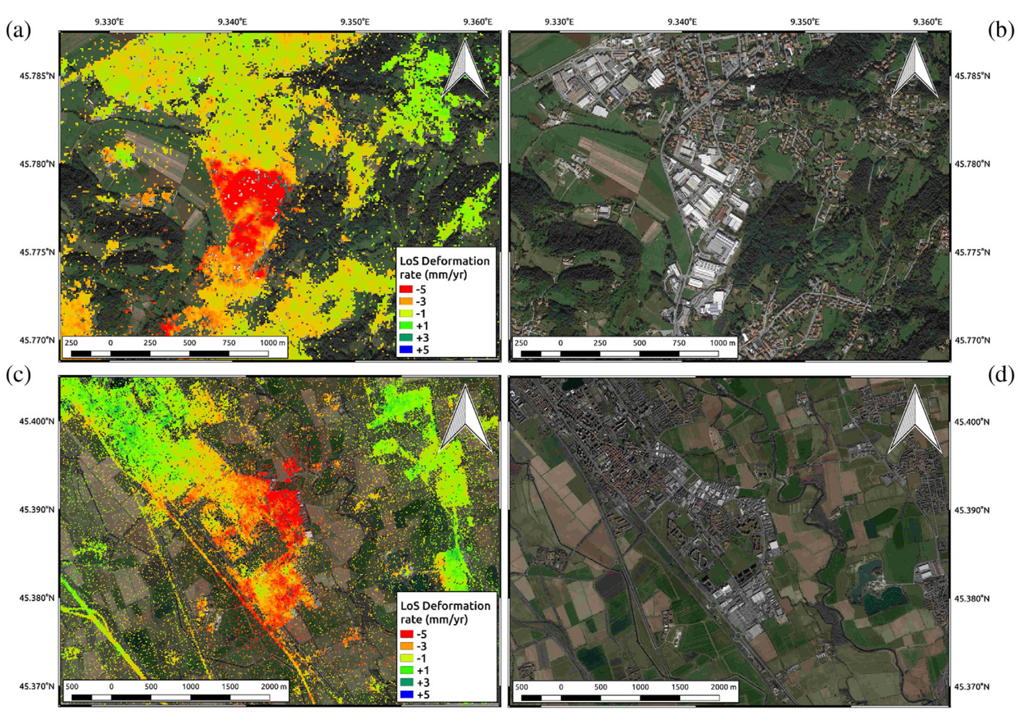

Fig. 5 (a) and (b) Oggiono and (c) and (d) San Giuliano M. case studies showing the influence of soil compaction effects in the observed subsidence because of the industrial expansion.

In the case of Valmadrera, the observed subsidence is most likely due to the combination of soil compaction effects because of the industrial expansion and the presence of active and ceased quarries, which occupy an area of about 35,000 m^2 along the Valmadrera town and surroundings. Particular care is required for Como case. The subsidence affecting the city is already known being due to natural phenomena mainly related to hydrogeological reasons. It is indeed located in a basin bordered by Lake Como and two tectonic lines, which delimit a narrow depression characterized by the large presence of alluvial soft sediments.[36] Therefore, in this case, the anthropogenic contribution, consisting of many reclaimed sites thus involving water pumping activities, only amplify natural subsidence phenomena.

Concerning Melzo case, the subsidence observed along the A58-TEEM highway is probably ascribable to the proximity of the quarry exploited for the excavation of the materials used for the construction of the A58-TEEM highway itself. Such quarry caused a ground level lowering during the construction and has been ceased in 2016 and transformed in a naturalistic oasis for the birdwatching.[41]

Finally, Verduggio is in the proximity of the Lambro river and very close to several quarries for the extraction of clay then the combination of these two factors could have contributed to the detected deformation pattern.

All these subsiding areas are resting on the railway and/or road lines, which are then subject to the highlighted phenomena. Apart from Verduggio and Oggiono cases, the other sites are reached by several lines of the nested connection network of Lombardia region referred to as Rete Ferroviaria Italiana (RFI). Therefore, we mainly focus here on a railway line but any considerations can be easily extended to roads and/or highways.

A common railway infrastructure (RFI) consists of a track, which includes both flat bottom rails and sleepers, and track foundation, i.e., ballast, sub-ballast, a protective layer and subgrade overcoming the natural ground layer (see the lower part of Fig. 6). Therefore, the affordable traffic on a railway line is strictly connected to the quality of both track and track foundation layers. In this context, the role of the sleepers is very important since they support the rails and transfer dynamic loads into the ballast. The pressure loaded by a train passage can produce a settlement of the ballast further resulting in a slight settlement in the underneath layers including natural ground.

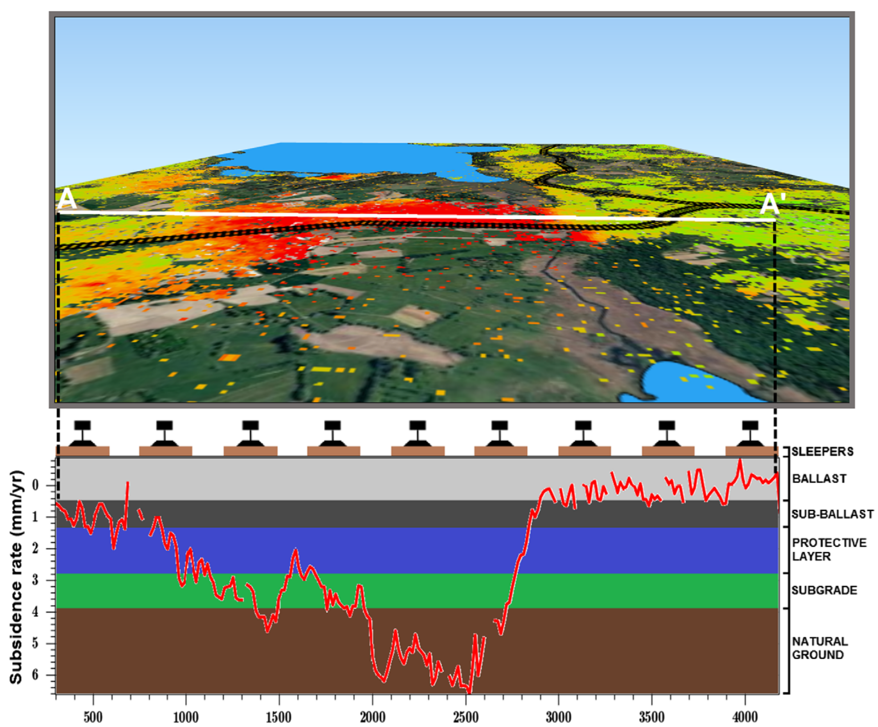

Fig. 6 Section of subsidence rate detected in the Erba case study indicated with AA' segment and superimposed on the section of railway line affected by the phenomenon.

The subsidence induced by external/independent natural or anthropogenic-induced reasons along a railway line produces a further loading on each layer. In particular, as possible to note by Fig. 6, this leads to a load gradient in correspondence of the boundaries of the subsidence pattern, proportional to the difference in deformation rate between stable and subsiding areas. This means that flat bottom rails and the sleepers in the proximity of the subsidence boundaries will be affected by different displacement fields, i.e., about 6 cm of difference in 10 years for most of the analyzed cases. Such deformation gradient can be also seen as different downward pressures, which, in extreme cases, can cause the railway line to collapse.[42]

On the other hand, highways and roads are generally composed of three layers overlying the natural soil subgrade. A flexible surface layer of hot-mix asphalt, a base layer consisting of unstabilized aggregates, asphalt, bitumen, or cement and a subbase layer constructed from local aggregate material, while the top of the subgrade is often made stable with cement or lime.

The flexible surface layer is designed for transferring the stress from the top of the surface to the layers below. Indeed, one of the properties of the asphalt is to slightly deform when subjected to a stress field and then return to its original position when it is removed. Depending on the conditions of the layer, some small deformations can become permanent thus causing problems to wheels of the transiting cars. The life cycle of such layer is typically 20 to 30 years according to traffic loads, thickness, environmental conditions, and so on.

Then, as for a railway line, if the subgrade is subsiding, a further stress field need to be taken into account when designing a maintenance service of highways and roads especially considering parts crossed by bridges or viaducts.

6 Conclusions

We exploited X-band Cosmo-SkyMed InSAR data characterized by revisit time spanning from 16 to 35 days to investigate several localized deformation phenomena occurring in the Lombardia region (northern Italy) and affecting the nested railway and road network crossing the region.

Our InSAR-based analysis shows how the large presence of anthropogenic activities, mainly related to the industrial expansion of the area, is inducing some subsidence effects, which could be potentially dangerous for some parts of railway and road infrastructure.

Indeed, the detected deformations show an almost linear trend peaking at about 6 to 7 mm/year that does not seem to be going to any slowdown. If persistent and/or accelerating, these subsidence phenomena could become very significant in a few years and affect these infrastructures leading to a considerable deformation gradient along the boundaries of the detected displacement patterns. The ground subsidence is only one of the sources of stress affecting railways and/or highways, which include train speed, mass of a vehicle, cargo, vibrations due to surface imperfections, slight oscillation of vehicles along yaw, roll and pitch, and so on.[43] However, discriminating between several causes and modeling future scenarios is not straightforward and is out of the scopes of this paper. Here, we want to point out the role and the possible exploitations of satellite remote sensing InSAR data for hazard assessment purposes in this application field especially considering the improved revisit time of 6 days obtained by Sentinel-1 missions of European Space Agency. Lombardia has already been interested by some train and road accidents and every day a million people move along the region. Therefore, in order to guarantee the safety of people, frequent monitoring of railway and road infrastructure including land conditions is strictly needed.

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