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Understanding the effects of tunneling on buildings by analyzing DInSAR data: the case of the new subway in Rome, Italy

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Abstract – Monitoring the displacements of the buildings during the execution of underground works is a very demanding activity in large urban areas contexts, due to the number of structures involved and to the duration of the measurements throughout the realization time. Therefore, the surface deformation detection cannot be based on direct measurements using ground-based sensors, only, and should include technologies that allow a systematic and comprehensive monitoring. The satellite DInSAR technique (Differential Interferometry Synthetic Aperture Radar) provides displacement time series of a large number of measuring points, which can be associated with different portions of a building and are able to reveal differential settlements. Furthermore, the availability of SAR data archived since 1992 allows performing back analyses to evaluate also long-term settlement processes not directly linked to the tunneling works. More recently, the COSMO-SkyMed constellation, developed by the Italian Space Agency (ASI), has provided data at higher space/time resolution, which have been profitably used to detect and follow the evolution of the settlements caused by tunneling excavation works, as in the case of the new metro line in Rome. By applying the advanced DInSAR methodology, we have estimated average rates of displacement for a number of buildings over the Metro C track interested by the subsidence, very likely triggered by tunneling. A classification-based approach was applied by taking into account the displacement rates and the associated statistical error parameters. This provided a tool for the direct identification of the most critical buildings that need further investigations.

I. INTRODUCTION

Ground settlements observed in the urban area can be related both to natural (ground settlements, subsidence, landslide phenomena) and anthropic (water pumping, excavations, underground works) processes impacting on the stability of civil structures and infrastructures. Monitoring the displacement of buildings during the execution of underground works is very difficult in large urban areas. In this context, the DInSAR (Differential SAR Interferometry) technique [1], [2] represents an efficient remote sensing technique able to monitor the displacements of isolated structures and infrastructures. It is based on the exploitation of the phase difference (interferogram) between two SAR (Synthetic Aperture Radar) images. The advanced DInSAR technique referred to as Small BAseline Subset (SBAS) approach [1, 2, 3, 4], applied to a large dataset of SAR images collected over an area of interest during a large time span, provides information on the temporal evolution of the displacements through the generation of deformation time series. The first generation of SAR data were available from 1992, with the ERS-1 ESA mission, followed by the Envisat one from 2002. These data archives are useful to implement back analyses to evaluate long-term settlement processes. The second generation of SAR systems (TerraSAR-X, COSMO-SkyMed, Radarsat-2) are characterized by an improved spatial resolution (of the order of a few meters) and a reduced revisit time (down to a few days) compared to the first generation systems, and play a key role in the control and analysis of the deformation phenomena of a single building.

This work focuses on the exploitation of the SBAS-DInSAR products (average velocity maps and time series of displacements) [1, 2, 3, 4] achieved by exploiting an ERS/ENVISAT (spatial resolution of about 30 m) and a COSMO-SkyMed (CSK) (spatial resolution of about 3 m) dataset. The SBAS-DInSAR products are analyzed to investigate the effects of the underground construction works in urban areas, which may represent a threat for the stability of the overlying structures. In particular, we

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intend to investigate the interactions between the building and the subway construction work of the third underground line in Rome (Metro C Line).

A classification-based approach is developed into a GIS (Geographic Information System) platform by applying the advanced spatial analysis over a DInSAR dataset, with the exploitation of other ancillary information.

II. STUDY AREA

The investigated area is located in the downtown of the city of Rome and involved the T2-T3-T4 (Fig.1) and part of the T5 sections of the Metro C line [6]. Some of the most famous monuments, churches and historic buildings are located over the tunnels of the new underground. Construction works of the T4 and T5 sections from San Giovanni to Alessandrino area started in April 2, 2007. The Metro C line is built at an average depth of 25-30 m under the ground level, into two single-track tunnels connected with the surface by stations and ventilation wells. Until now, 4,300,000 m^3 of soil and over 29 km of tunnels have been excavated, using 270,000 tons of steel, 1.6 million m^3 of concrete, 7,400 tons of rails, 150 tons of copper for the power line, and 110 km of cables.

Fig. 1. T2-T3-T4 and part of the T5 *Metro C tracks, superimposed on an optical image of the Rome urban area.*

III. AVAILABLE DATA

The available datasets include 131 ERS/ENVISAT SAR scenes collected between 1992 and 2010 and 38 Cosmo-SkyMed scenes acquired between 2010 and 2012. The SAR data were processed using the multi-scale and multi-temporal SBAS approach [1, 2, 3, 4]. This technique allows detecting the displacements of a single scatter point (PS) occurred during a certain time span. The results obtained through the SBAS approach were analyzed in order to obtain average velocity maps (AVM). In Fig. 2A and 2B we show the AVMs obtained from the analysis of the 1992-2010 ERS-ENVISAT and the 2010-2012 COSMO-SkyMed (CSM) datasets, respectively. The deformation trends shown in the AVMs appear in a general good agreement, although it is evident an increased number of detected PS for CSK analysis, due to the improved spatial resolution of the CSK system, see tab.1.

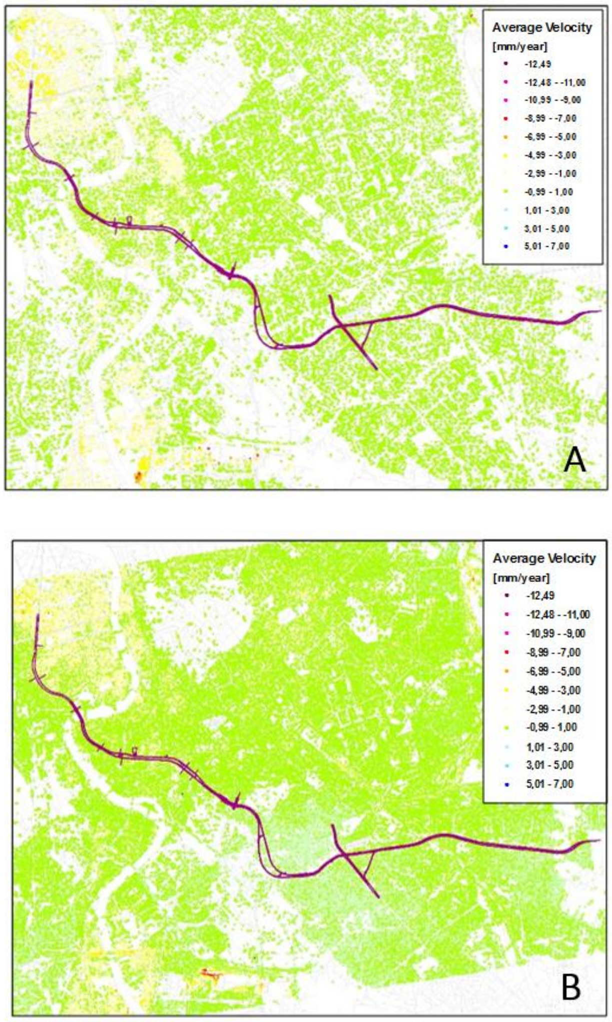


Fig. 2 Results of the SBAS-DInSAR analysis achieved on the studied area using the 1992-2010 ERS-ENVISAT (A) data and the 2010-2012 CSK data (B). The T2-T3-T4 and part of the T5 *Metro C tracks are also pictured.*

Table 1. Data density in the city of Rome

Dataset	Points/Km^2
Ers-Envisat	**3254**
Cosmo-SkyMed	**26894**

IV. BUILDING CLASSIFICATION MAPS

A classification-based approach of buildings along the Metro C track was carried out. The investigated area involves the corresponding surface on the tunnel path, with variable width between 150 m and 350 m, in relation to the depth of excavation works and the nature of the traversed terrains (Fig. 3). A GIS-based tool was developed to spatially correlate and statistically analyze the DInSAR average velocities, in order to extract classification parameters to be assigned to each building. A proximity analysis was applied to associate a set of PS to single structures, considering buffer zones around them. The buildings were classified using different parameters, such as the number of measured points, the displacements rates (annual average velocity) and the associated statistics

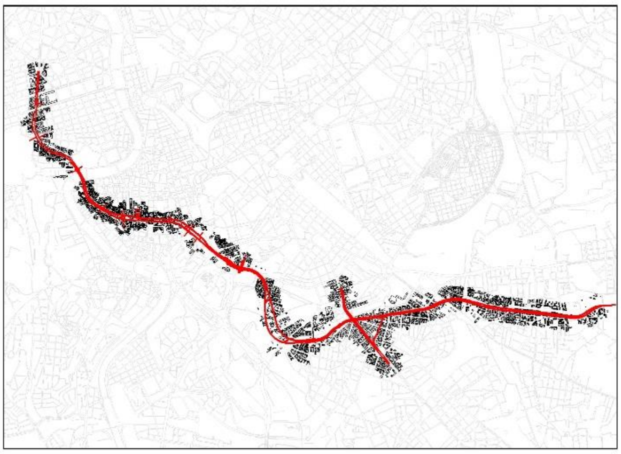
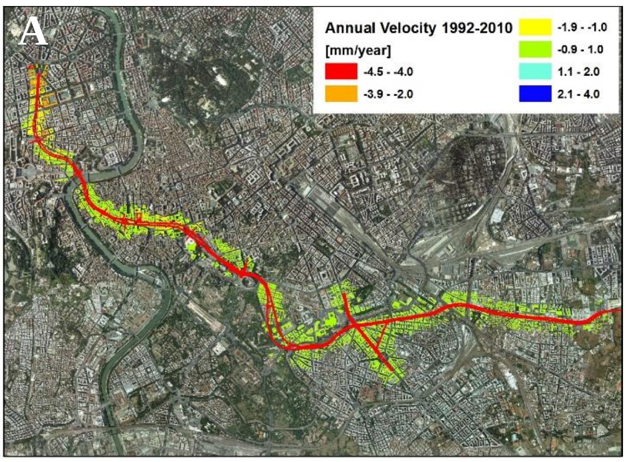


Fig. 3. Selected buildings along T2-T3-T4 and part of the T5 *Metro C track.*

A combined analysis of these parameters was carried out in order to assess the reliability of the estimated trends and to individuate different behaviors of settlements related to the investigated buildings. The analysis allows to identify differential displacements that can affect the structures and represent a plight for their stability. Fig. 4 shows an example of classification map obtained using the GIS-based tool. In order to better understand the ongoing phenomena, the analyses were focused on three different parts of the Metro track: Zone A, Piazza Mazzini; Zone B, Historical Center; Zone C, San Giovanni (Fig. 5).



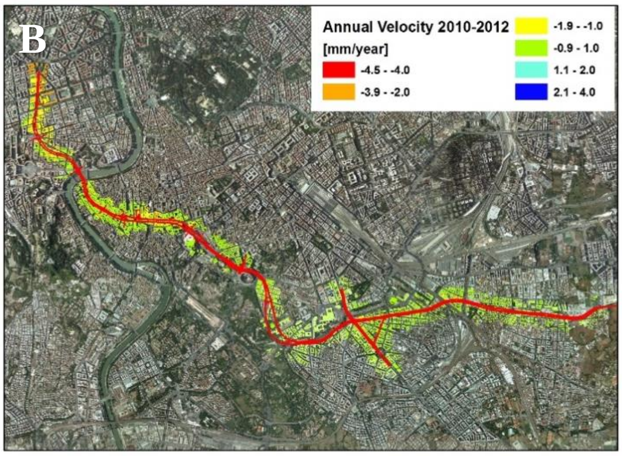


Fig. 4. Classification maps obtained by analyzing the ERS-ENVISAT 1992-2010(A) and the COSMO-SkyMed 2010-2012 (B) DInSAR data along T2-T3-T4 and part of the T5 *Metro C track.*

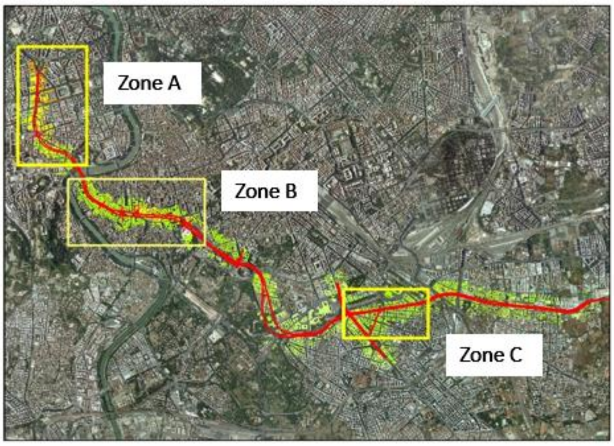


Fig. 5. Classification map. Yellow boxes show analyzed areas: A (Prati), B (Historical Centre) and C (San Giovanni).

The classification maps obtained by processing the ERS-ENVISAT dataset (1992-2010) cover the period before the excavation works, while the classification maps obtained by processing the COSMO-SkyMed dataset (2010-2012) cover the period after the excavation works in zone C.
Comparing the classification maps obtained for the three areas for different time span (1992-2010 and 2010– 2012), we can see that:

- Zone A and Zone B do not have different behaviors, in fact these areas have not been yet involved in work excavations. The observed settlements could be linked to other causes, such as geological setting, structural characteristics etc., which are not investigated in this work [5];

- Zone C was involved in work excavations in

2010; in this areas the two datasets highlight different behaviors on some buildings characterized by an increase of displacement average velocity (fig.6).

Fig.6. Classification maps for the studied areas (A, B and C) obtained by analyzing the ERS-ENVISAT and the COSMO-SkyMed DInSAR data.

V. IDENTIFICATION AND ANALYSIS OF THE CRITICAL ISSUES

Starting from the classification maps, critical buildings were identified, and the average trends of displacement time series considering all the PS on the structure were estimated.

A joint analysis of the average displacement time series and the phases of excavation work was carried out. In particular, a detailed study was carried out for a building located in Zone C. Figure 7 shows a detailed view of the classification maps and the displacement time series obtained using the two different datasets (ERS-ENVISAT and COSMO-SkyMed) for the investigated building. As shown in the classification maps, the analyzed building belongs to a class between -0.9-1 mm/y (i.e. stable building) during the period 1992-2010, while during the 2010-2012 period the same building belongs to a class characterized by a velocity of -2 -3.9 mm/y. Analyzing the time series jointly with the beginning of the excavation works, we can see that the displacement velocity increases in conjunction with the excavation work from 20/09/2010 to 08/06/2011 and is still ongoing.

The results of this analysis highlight a possible link between the excavation works and the increase of displacement velocity.

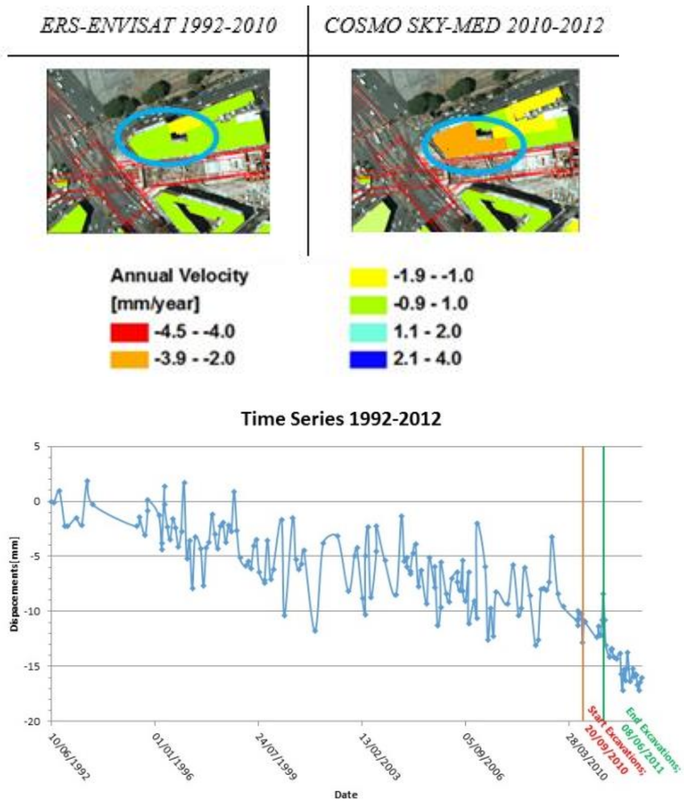


Fig. 7. Classification Map and displacement time series relevant to a building located in Zone C .

VI. CONCLUSIONS

The control of the stability of the buildings in large urban areas represents one of the main issues concerning the safety of the population. The security of a building is often threatened by natural and/or anthropic processes, which can affect the stability of the structures. Monitoring large areas using traditional surveying techniques is not possible both from the point of view of the costs and the extension of the area to investigate. Remote sensing technologies allow a systematic non-invasive monitoring of large areas. Among the different remote sensing technique, the satellite Differential SAR Interferometry (DInSAR) allows the monitoring of the displacements affecting the buildings with a millimeter-centimeter accuracy. Buildings provide a number of reflective elements that represent "natural" control points for DInSAR measurements, due to their physical and geometric characteristics. This makes this technique particularly suitable in cases of monitoring of historical monuments, because no reflector installation on the structure is needed. An important aspect of this method is the capability to perform back analyses since 1992, thanks to the availability of archive SAR data of ESA. For this reason, this monitoring technique demonstrated to be an efficient method to analyze the behavior of a structure. In this work, the DInSAR data were exploited using a GIS-based tool to automatically detect critical phenomena due to anthropic activity. This approach can be useful to support the definition of the preventive actions aimed at improving the safety of the structures.

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