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SATELLITE A-DINSAR MONITORING OF THE VITTORIANO MONUMENT (ROME, ITALY): IMPLICATIONS FOR HERITAGE PRESERVATION

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EXTENDED ABSTRACT

Questo lavoro è il risultato di uno studio condotto in collaborazione tra il Centro di Ricerca (CERI) dell'Università di Roma La Sapienza e il Polo Museale del Lazio, con la collaborazione di ISPRA, dedicato allo studio dell'assetto geologico-tecnico del sottosuolo e all'analisi degli spostamenti per la definizione dei processi di interazione terreno-struttura riguardanti il monumento a Vittorio Emanuele II.

Nell'ambito di tale collaborazione, sono stati oggetto di specifica indagine i seguenti aspetti: i) la ricostruzione della geometria e del piano di posa degli elementi fondazionali che sostengono il monumento e la definizione del modello geologico del volume di sottosuolo interessato dalla trasmissione del carico di fondazione; ii) l'analisi dei tassi deformativi attraverso tecniche Advanced Differential Synthetic Aperture Radar Interferometry (A-DInSAR); iii) l'esame delle correlazioni tra i due aspetti sopracitati nella definizione delle possibili cause dei dissesti strutturali in corrispondenza dell'ala ovest del Monumento che, a partire dal muro perimetrale esterno, attraversano numerose sale disposte su più livelli.

Il Monumento a Vittorio Emanuele II, conosciuto come Vittoriano, è uno dei simboli patri italiani e ne rappresenta l'identità nazionale. Ideato e progettato dall'architetto Giuseppe Sacconi, fin dalle prime fasi di realizzazione il Vittoriano ha necessitato di varianti progettuali in sede esecutiva ed è stato interessato da dissesti e lesioni che già dai primi anni del '900 hanno condotto al susseguirsi di differenti interventi di consolidamento. In questo contesto, al fine di ricostruire il campo di deformazioni subite negli ultimi decenni (2002-2019) dal Monumento, si è fatto ricorso all'uso di tecniche di monitoraggio da remoto, note come InSAR (Interferometric Synthetic Aperture RADAR). Il principio alla base delle metodologie Multi-Image InSAR o Advanced DInSAR (A-DInSAR) specificamente utilizzate, è costituito dalla combinazione delle informazioni di "fase d'onda" provenienti da un elevato numero di immagini radar, che permette la ricostruzione di serie temporali di spostamento di oggetti a terra ben visibili dal satellite. L'archivio di immagini satellitari elaborato fa riferimento al satellite ENVISAT dell'Agenzia Spaziale Europea per il periodo 2002-2010 e alla costellazione COSMO-SkyMed dell'Agenzia Spaziale Italiana per il periodo 2010-2019. La tecnica A-DInSAR si basa sull'analisi di oggetti molto "stabili" da un punto di vista radaristico e naturalmente presenti nell'area d'interesse. Risulta, dunque uno strumento dalle potenzialità uniche per il monitoraggio di strutture complesse, soprattutto grazie alla capacità di fornire informazioni su territori di vaste dimensioni, con elevata risoluzione spaziale (alcuni metri) e precisione millimetrica.

La possibilità di disporre di un dataset esteso ha permesso di inquadrare il Vittoriano all'interno di un contesto più ampio e studiarne i trend deformativi anche in funzione delle informazioni circostanti. Al fine di estrapolare il massimo delle informazioni dai risultati ottenuti, nel presente studio si è cercato di oltrepassare la canonica precisione di misura (stimata da letteratura nell'ordine dei ±1,5 mm/anno), effettuando una forzatura nella restituzione del dato interferometrico ottenuto. Questo processo è stato coadiuvato dalla dettagliata ricostruzione dell'assetto geologico-tecnico dell'area in esame, condotta attraverso lo studio dei dati ottenuti in molteplici campagne di indagine, del materiale storico, archivistico, bibliografico e attraverso sopralluoghi anche all'interno del reticolo caveale interno al colle. Alla luce della ricostruzione geologico-tecnica, l'analisi dei campi deformativi nell'area di studio evidenzia due zone a diverso comportamento deformativo: una sud-orientale, non soggetta a grandi deformazioni e pertanto considerata stabile, e una nord-occidentale che mostra diversi punti di misura con trend deformativi di lungo periodo, con velocità di spostamento stimate nell'intervallo tra -0,3 e -1,5 mm/anno. Tale eterogeneità di comportamento risiede nella complessità geologica dell'area. In particolare, si evince come i punti di misura più stabili siano localizzati in corrispondenza di corpi geologici litoidi, sui quali fonda la parte meridionale del Monumento, mentre le maggiori deformazioni si concentrano nell'area che ospita formazioni alluvionali compressibili. È stato quindi possibile riconoscere nel fenomeno di cedimento differenziale delle fondazioni di un'opera così voluminosa, una probabile causa della comparsa e persistenza delle lesioni nel muro perimetrale occidentale. La rappresentazione utilizzata, che sfrutta oltre il limite strumentale la metodologia A-DinSAR, restituisce un quadro deformativo del tutto coerente con le informazioni sull'assetto geologico-tecnico del sottosuolo del Vittoriano; la coerenza tra informazioni indipendenti costituisce una conferma indiretta circa la ragionevolezza della forzatura adottata nell'elaborazione dei dati interferometrici e dell'importanza del dato telerilevato ai fini di una migliore definizione della geometria dei corpi geologici superficiali e dei processi evolutivi a cui sono soggetti.

ABSTRACT

The "Vittoriano" monument, dedicated to king Vittorio Emanuele II, is one of the most famous cultural heritage landmarks in Rome (Italy), even because it hosts the Tomb of the unknown soldier, monument to the Italian fallen in wars. It was designed by the architect Giuseppe Sacconi at the end of 19th century and since the beginning of its construction, it has been affected by cracks and deformations. In the last years, such phenomena have become more evident, especially on the western side of the building. With the aim of understanding the causes of the deformation process and making a diagnosis of the soil-structure interaction of the Monument, a specific project has been undertaken between CERI Sapienza and the Lazio Museum Network.

Satellite ADInSAR was performed to infer the recent deformational history of the main parts of the monument, by using medium and high-resolution SAR images acquired in double orbital geometry (ascending and descending) and covering the last two decades.

Through the support of selected geological and lithotechnical data it was possible to interpret the deformational dynamics of the Vittoriano.

The overall investigations allowed to better define the volume and the structures that have been involved in the deformation mechanisms, which is currently driving the overall process, in order to address effective mitigation measures. They are capable of backward analysing the deformational process, reconstructing the evolution of a phenomenon and above all capable of easily investigating large areas.

Keywords: *Vittoriano, InSAR monitoring, cultural heritage, engineering geological investigations*

INTRODUCTION

Rome is the city with the highest concentration of archaeological, historical, architectural and archival assets in the world, and preserves a stratification of uninterrupted life that spans along almost three millennia. Monitoring and conservation of these assets is often complex and requires a wide range of operations to define the risk condition of each of them.

Unfortunately, risk scenario assessment of cultural heritage sites is currently carried out downstream of a catastrophic event. This, in addition to undermining people safety, involves high costs related to restoration and reconstruction.

It is therefore necessary to enforce the prioritization of monitoring and conservation policies to ensure sustainable conservation. Monitoring the deformation of structures as well as their surroundings facilitates the early recognition of potential risks and enables effective conservation planning (Tang *et alii*, 2016). In cities, such as Rome, where the artistic and archaeological heritage is very extensive and developed, it may be necessary to adopt non-invasive monitoring techniques. Among these, Satellite SAR interferometry and in particular the Advanced Differential Synthetic Aperture Radar Interferometry (A-DInSAR) technique is a tool with unique potential for structural monitoring, as it can provide information on the surface deformations of soil and structures, with millimetric precision and with good spatial resolution (Rocca *et alii,* 2013). In particular, the A-DInSAR techniques, thanks to the archive radar images available since the early 1990s, provide the unique opportunity to investigate the conditions of structure back in time, studying the history of structural deformations from a quantitative point of view also covering large areas (Wang *et alii*, 2011; Tomas *et alii*, 2013). The use of time series has become a precise and cost-effective solution, assisting the conventional monitoring systems. The correlation of geological and structural information with satellite radar monitoring constitutes a fundamental reading key for the study of processes that can affect the stability of structures of significant cultural value. Monitoring activities (both satellite and ground-based) can be very useful for cultural heritage management, allowing to identify and control possible structural deformations or critical behaviours. In particular, this study, starting from the reconstruction of the geological model of the subsoil, is focused on the application of this technique (A-DInSAR) for the analysis of the deformation processes involving the monument dedicated to king Vittorio Emanuele II (historic center of Rome) (Fig. 1).

BASIC PRINCIPLES OF SAR INTERFEROMETRY AND ADVANCED DIN-SAR

Interferometric Synthetic Aperture Radar (InSAR) (Massonet *et alii,* 1998; Hanssen Ramon, 2001), based on the comparison of Radar images acquired at different times, represents the main satellite remote sensing methodology used nowadays to measure displacements of the earth's surface and its structures.

The principle behind the Multi-Image InSAR or Advanced DInSAR (A-DInSAR) methodologies is the combination of information from many images, which allows the reconstruction of time series of moving objects on the ground clearly visible from the satellite in the whole analysed period.

The use of A-DInSAR techniques allows not only to identify a given deformation process, past or in progress, but also to estimate its evolution over time and space. The A-DInSAR technique is based on the analysis of very "stable" objects, from a radar point of view, naturally present in the area of interest. These targets, characterized by a high-quality radar signal over time, represent real interferometric measurement points (MP) (Kampes, 2006).

Interferometric Analyses

The choice of satellite SAR images was guided by the need to ensure an adequate temporal coverage of historical archive data (time frame 2002–2019) and enough quantity of images (stack) for

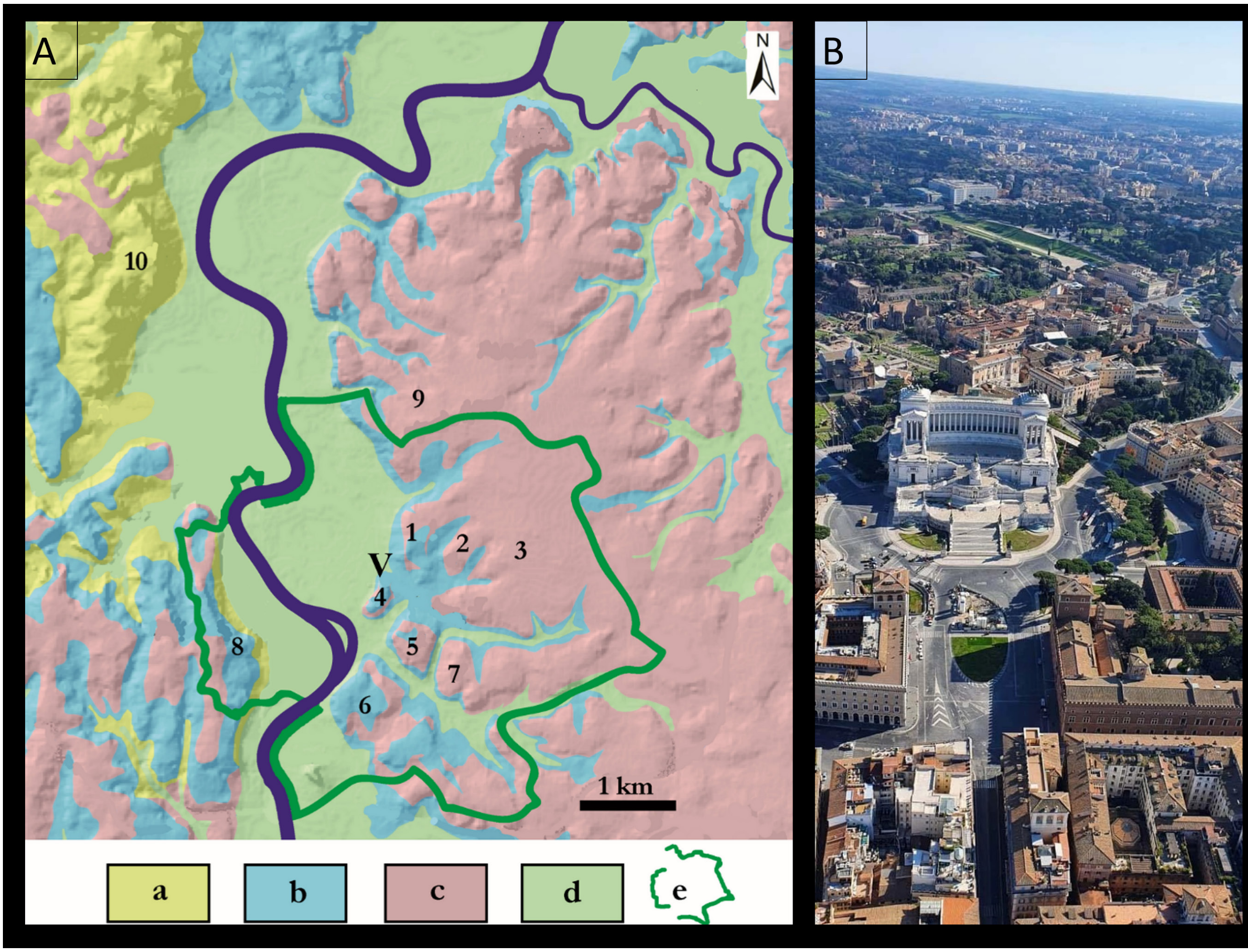

Fig. 1 - A) Hill-shade lithological sketch of Rome urban area. Legend: a) marine deposits b) continental sedimentary deposits, c) pyroclastic rocks, d) post-Wurmian alluvium, e) city center. Hills: 1) Quirinale, 2) Viminale, 3) Esquilino, 4) Campidoglio, 5) Palatino, 6) Aventino, 7) Celio, 8) Gianicolo, 9) Pincio, 10) Monte Mario. V: Vittoriano. (modified after: VERGARI et al., 2020). B) Southward view of Piazza Venezia during the Covid 19 pandemic with the Vittoriano Monument clearly visible

the type of study (Tab. 1). In order to minimize the effects related to geometric distortions, typical of satellite SAR data, and to better characterize any deformation processes in the study area, data have been acquired both in ascending and descending orbital geometry.

For both ENVISAT and COSMO-SkyMed data, large-scale analyses were performed on a portion of the SAR images frame of approximately 0.3 km^2, carrying out a conventional PSI approach, according to FERRETTI *et alii* (2000, 2001).

For ENVISAT data (European Space Agency-ESA), a total of 90 SAR images have been acquired in ASAR Image Mode, characterized by a spatial resolution of approximately 30 meters and a wavelength of 5.6 cm (C-band). These are distributed as follows:

- 47 Single Look Complex (SLC) images acquired in ascending orbital geometry from November 16th, 2002 to August 21st, 2010
- 43 Single Look Complex (SLC) images acquired in descending orbital geometry from November 10th, 2002 to June 6th, 2010

InSAR Set	Number of Scenes	Acquisition Period
ENVISAT (Ascending)	47	2002–2010
ENVISAT (Descending)	43	2002–2010
COSMO_SkyMed (Ascending)	138	2010–2019
COSMO_SkyMed (Descending)	106	2011–2019

Tab. 1 - SAR datasets used in this work

For COSMO-SkyMed data (Italian Space Agency—ASI), a total of 244 SAR images have been acquired in Strip Map HIMAGE mode, with a spatial resolution of about 3x3 meters and a wavelength of 3.1 cm (X-band). These are distributed as follows:

- 138 Single Look Complex (SLC) images acquired in ascending orbital geometry from July 4th, 2010 to February 23rd, 2019

- 106 Single Look Complex (SLC) images acquired in descending orbital geometry from July 29th, 2011 to February 25th, 2019

The four stacks of ENVISAT and COSMO-SkyMed images, ascending and descending, were analysed separately through a workflow. It comprises A-DInSAR methodologies with an added validation and post-processing activities of the results, useful to provide an interpretative reading of A-DInSAR data. All procedures were implemented in Sarproz (Perissin *et alii,* 2011), a software developed for multi-image InSAR analyses with the PS-InSAR technique.

A useful auxiliary tool for the execution of interferometric analyses was represented by the digital elevation model (DEM) which provided basic information relating to the altitude of the study area and allowed the geocoding of the results. For this study, the DEM SRTM (Shuttle Radar Topography Mission) with 30 m of spatial resolution was used.

At the end of the PS analyses, the final results have been selected by applying a high temporal coherence threshold, thus selecting only pixels characterized by a temporal coherence greater than 0.6 to attain only reliable time series both for ENVISAT and COSMO-SkyMed datasets.

GEOLOGICAL FRAMEWORK

Geological overview of the Roman area

The territory of the municipality of Rome is characterized by rock and soil successions lithologically heterogeneous (Fig. 1A). These are the product of both exogenous and endogenous activities and reflect a complex geological history that developed in several depositional environments and was conditioned by glacio-eustatic sea-level changes, volcanic eruptions and tectonic processes (Marra & Rosa,1995; Ventriglia, 2002; Funiciello & Giordano 2008; Luberti *et alii*, 2017). Starting from Pliocene, the geological history of the Roman area can be summarized in four main phases:

- sedimentation in a circalittoral marine basin, from Middle Pliocene to Early Pleistocene (Parotto, 2008);
- sedimentation in an infralittoral marine basin, during Early Pleistocene (Marra & Rosa, 1995; Luberti *et alii*, 2017);
- transitional and continental sedimentation with stratigraphic sequences mainly driven by sea-level changes that alternate with volcanic deposits, over Middle Pleistocene (Milli, 1997; Marra *et alii*, 1998);
- Last-Glacial landscape modelling by the Tiber river hydrographic network and the Holocene fluvial sedimentation (Bozzano *et alii*, 2000; Milli *et alii*, 2016).

During this last period, the interplay between regional uplift and sea level fall enforced the erosive processes of the Paleo Tiber (Luberti *et alii*, 2017); as a consequence, its hydrographic network incised deep valleys in volcanic and sedimentary deposits, often down to the pliocenic marine bedrock (Marra & Rosa, 1995; Parotto, 2008; Luberti *et alii,* 2017). This is the situation of the wide Tiber paleo-valley that runs N-S through the city center of Rome, where its bottom can reach even depths of 50 m below the present sea level (Marra *et alii*, 2013).With the end of the Last Glacial (about 13,000 years ago) and the progressive sea-level rise, the Tiber filled the valley incisions with alluvial and palustrine deposits, up to 60 m thick, and it reached the current base level about 2,300 years ago (Marra *et alii*, 2018). According to Milli *et alii* (2016) and Bozzano *et alii* (2000), this sedimentary body is composed of a gravel basal horizon that correlates with the late glacial low stand, followed upwards by a sequence of smooth sands and clays with strong heteropy. Bozzano *et alii* (2000) defined at least 4 lithotypes into this geological body; among them, only the lithotype C (clays and grey-black layers, with levels enriched in organic substance and rare sandy levels) has been found near Piazza Venezia.

Geological and geomorphological setting of the Capitoline Hill (Campidoglio)

During the last glacial, about 18,000 years ago, the Tiber River deeply incised the volcanic plateau and interdigited sediments, so carving those hilly reliefs that, particularly on the less elevated left bank, represent the typical roman landscape. The Capitoline Hill, between the Tiber and its tributary Spinon in the Velabrum valley, is one of the historic seven hills on which the city of Rome was founded. Currently, it looks like a modest relief NNE-SSW elongated, which has two peaks, the Arx to the North and the Capitolium to the South; they are connected by a saddle that houses Piazza del Campidoglio (Fig. 2). Its slopes are made of lithified pyroclastic rocks, which can sustain high slopes, as the legendary “Rupe Tarpea” on the SE side, and the one on the W side.

Instead, the surrounding plain partially belongs to the alluvial plain of the Tiber and its tributary, as well as in the northern side it is the result of the ground levelling operated since the Roman age (Corazza *et alii*, 2004; Vergari *et alii*, 2020). However, these plains are actually buried by anthropogenic deposits, also commonly referred as the “archaeological layer”, which in the Velabrum valley reach nearly 20 m in thickness (Ammerman *et alii*, 2008).

The stratigraphy of the Capitoline Hill has been a debated topic in literature. We chose to take into account the most recent works about the geology of the hill, including Alvarez *et alii* (1996), Corazza *et alii* (2004), Luberti *et alii* (2017), Mancini *et alii* (2018) and Chiocchini *et alii* (2018).

In the context of our study, in addition to the outcrops

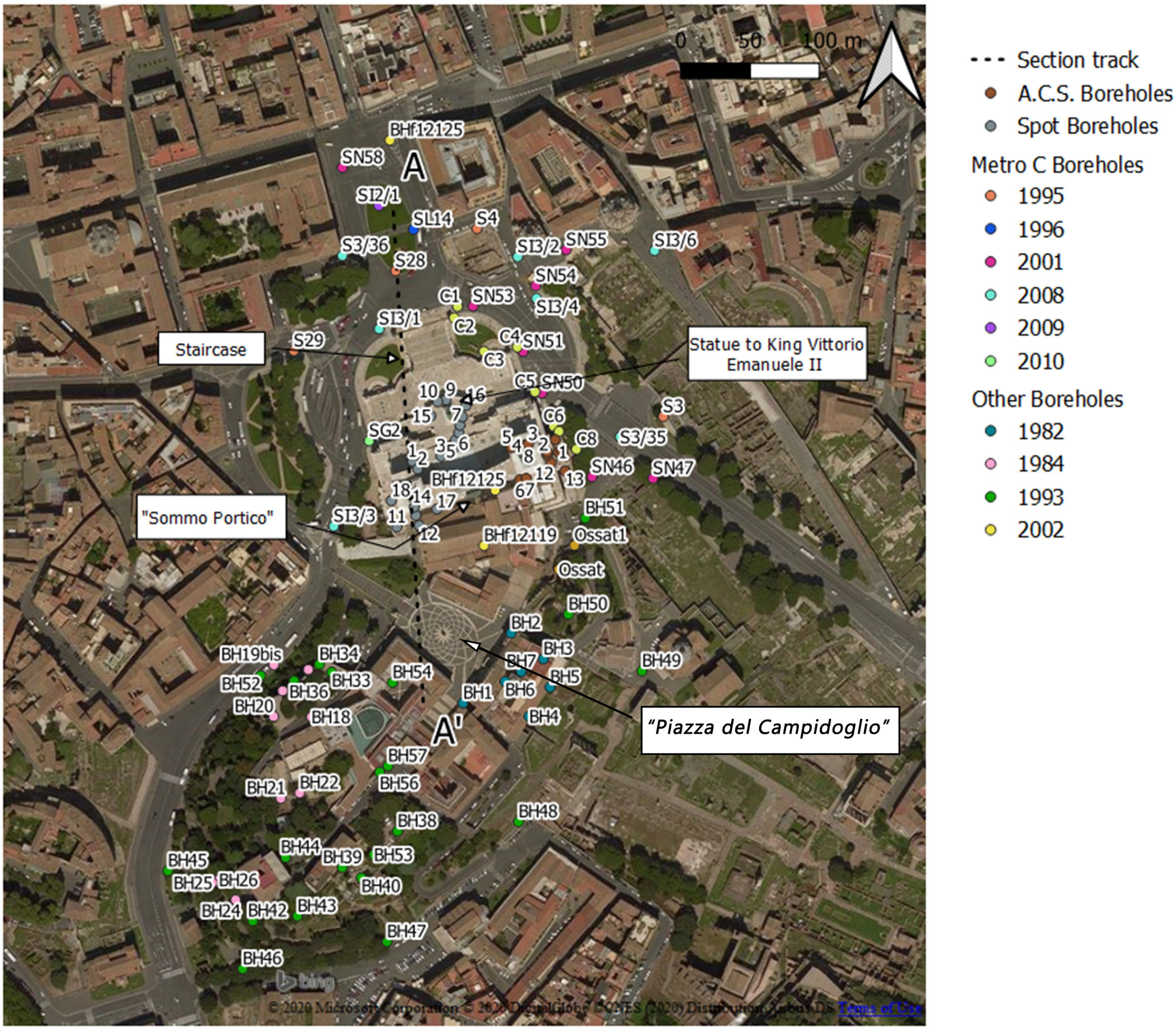

Fig. 2 - Location of the examined boreholes and track of the geological section A'-A of Fig. 4

studied by previous authors, further geological information were obtained from the consultation of projects, data, photographs, and diagrams contained in archival and historical reports (De Angelis D'Ossat, 1932; Metro C S.P.A., 2010a, b, c, d, e; Portis, 1893).

Some of the above-mentioned documents were produced during the construction of the Monument. Geognostic boreholes realized over the last few decades for various purposes, including their logs and the photographic records of the cores, are available (Archivio Centrale Dello Stato, 1871-1924; Sappa & Asquini, 1998; METRO C S.P.A., 2010 f, g).

More than 109 stratigraphic logs were considered for the reconstruction of the geological settings of the area. Metro C S.p.A. (2010a) provides a plan with the geometric-structural survey of the underground network of cavities from which the elevation and the position of about 10 geological reference spots have been extracted. Underground cavities are linked to ancient mining works, dating back to the republican and imperial roman ages. They were used to provide construction materials.

The analysis of bibliographic data, as well as these additional data useful for geological purposes, let us to populate a dataset (Fig. 2), able to produce an accurate 3D engineering geological model of the Capitoline Hill not dealt in this paper.

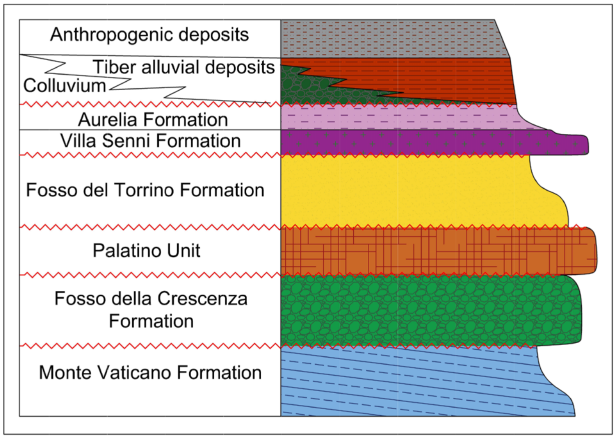

Fig. 3 - Stratigraphic column of the Arx (Capitoline Hill)

Stratigraphic succession and geological setting of the Arx

The stratigraphic succession of the northern part of the Capitoline hill named "Arx", which hosts the Vittoriano monument, is represented (Fig. 3) by the following formations and recent deposits (referring to the official stratigraphy reported in the "Foglio 374 Roma" given by Funiciello & Giordano, 2008 https://www.isprambiente.gov.it/Media/carg/374_ROMA/Foglio.html).

- Monte Vaticano Formation (Pliocene-Early Pleistocene): blue-grey overconsolidated clays with silty or sandy intercalations (with high Nspt values);
- Fosso della Crescenza Formation: gravels and sands with limestone or flint pebbles. It is located above the erosive surface of the Monte Vaticano Formation. According to Corazza *et alii* (2004), this formation is part of the Paleotevere deposition system, specifically the Paleotevere 2 (sensu: Marra & Rosa, 1995);
- Palatino Unit: massive and predominantly dark grey lithified pyroclastic deposits emitted from the Alban Hills volcanic district (Karner *et alii*, 2001);
- Fosso del Torrino Formation: fluvial yellow to green sands with both silty and fine gravelly levels, containing horizons of reworked volcanic material rich in pumice. These deposits, that are up to some tens of meter thick in the northern side of the hill, include several facies typical of fluvial sedimentation;
- Villa Senni Formation: massive pyroclastic-flow unit, in which there is a lithified tuff facies, orange to yellow in colour, rich in scoriae included in an ash matrix, with pozzolanaceous levels in the upper part of the formation (Freda *et alii*, 1997). It outcrops along the slopes of the hill, and it increases in thickness from east to west, having filled a paleovalley incised during MIS 10 (Corazza *et alii*, 2004);
- Aurelia Formation: silts and clay with travertine concretions; it outcrops at the top of the south-eastern sector of the hill (Capitolium);
- Colluvium: Corazza *et alii* (2004) reported that a Tufo Lionato block was detected by a borehole in Piazza Venezia, overlain by some tens of meters of alluvial deposits, and so they interpreted it as part of late pleistocenic-holocenic gravitational deposits from the slope of the hill;
- Tiber alluvial deposits: fine-grained deposits, predominantly silts and clays low to mid consolidated, with peat intercalations;
- Anthropogenic deposits: according to geognostic boreholes, there is evidence of a thick layer, sometimes more than 15 meters thick, which covers the Tiber and the tributaries' plains, as well as the top of the Capitoline Hill and somewhere its slopes. They are loose, heterogeneous deposits in sandy-silt matrix. They mainly consist in reworked pyroclastic materials and contain fragments of tuffs, marbles and bricks.

The geological setting of the subsoil of the Vittoriano monument provides a remarkable insight into the upper Pliocene-Pleistocene and Holocene evolution of the Roman area. Despite the local succession lacks most of the units outcropping in the Roman area, it is arranged in a very complex 3D geometry made of the

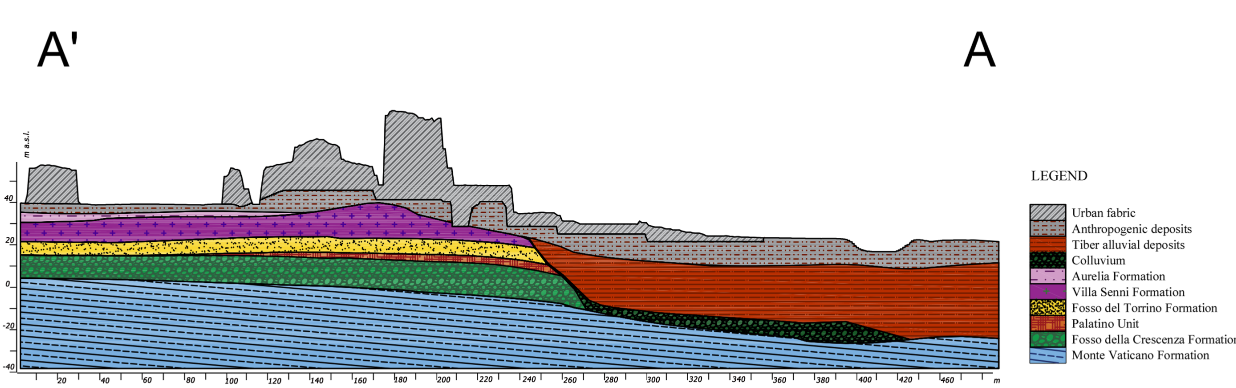

Fig. 4 - Geological cross section (track in Fig. 2). Topography derived from DSM provided by Ministry of Environment

formations and recent deposits described above. The geological cross section of Fig. 4 help us to describe this arrangement.

In the Arx area, the bedrock is constituted by the Monte Vaticano formation. Its top surface depth increases toward Piazza Venezia, because of the Last-Glacial deep valley incision of the Tiber river, which was partially filled by alluvial deposits up to 60 m thick (as in the right part of the geological cross section of Fig.4). In the subsoil of the staircase of the Vittoriano monument located in the northern part of the Arx, under the thick anthropogenic deposits, there are the Tiber alluvial deposits. Conversely, in the subsoil of the southern and central part of the edifice ("Sommo Portico", the highest sector of the monument and the area of the equestrian statue) the pleistocenic fluvio/continental and volcanic terms of the stratigraphic succession lay above the Monte Vaticano formation. The 3D geometry of these continental units under the compound is very complex, because of their depositional features: for example, on the eastern side of the Monument the Fosso del Torrino formation is very thick, while on the western one it is very thin or even lacking; this confirms the presence of a paleovalley located E of the Capitoline Hill, as suggested by Mancini *et alii* (2018). Similarly, the thickness of the Villa Senni formation is variable, having the maximum value below the western side of the Sommo Portico, and lacking or being very thin on the eastern side, as well as below the staircase. Here, since the Last Glacial the volcanic formation was cut by the fluvial erosion and gravitational processes, which shaped the northern slope of the Arx.

THE MONUMENTAL COMPLEX OF THE VITTORIANO

In 1870, just after Italy unification, the area corresponding to the city of Rome was a large countryside with limited concentrations of villas and rural houses, with the exception of the Tiber plain. On the eastern side of the Tiber, the urbanization was spread between Campo Marzio and Piazza del Popolo and the inner hills. During this period, it was conceived to erect the national monument dedicated to king Vittorio Emanuele II, a colossal building made to symbolize the birth of the Italian State. It also hosts the so called Altar of the Fatherland (Altare della Patria). The construction started in 1885, some years after the king's death, based on the design by the architect Giuseppe Sacconi (1856-1905).The project required a terrace on the north side of the Capitoline hill located about 27.50 meters above the Piazza Venezia level (about 47.5 m a.s.l.) where to place, in the centre, the statue to king Vittorio Emanuele II, and behind it a portico beside the Ara Coeli church. The monument was inaugurated by Vittorio Emanuele III, in the occasion of the 50th anniversary of the Unity of Italy (1911), but it was completed only in 1935, after several adjustment works. The huge construction site caused the expropriation and demolition of many medieval and Roman constructions previously located on the Arx, upsetting the city plan and hill topography. To investigate the soil-foundations interaction, we reconstructed the characteristics and depths of the foundation elements.

The actual depth of each pylon, numbered from I to VIII, a, b, as well as the western and eastern perimeter walls, was inferred according to sketches from the A.C.S. files and through the analysis of original documents and stratigraphic log C# (from C1 to C8), SG2 boreholes (Metro C 2010) (Fig. 5). Based on the above mentioned files, the founding elements of the "Sommo Portico" and the perimeter elements of the monument turn out to be made up of rectangular-based plinths, filled with stone and flint, connected by arches.

They are probably due to the inaccurate knowledge of the heterogeneity of the foundation soils and to the presence of underground cavities. The cracking pattern currently detected on the Monument can be traced back to the first joint that occurred at the beginning of the monument construction. The whole cracks pattern was subject to static and dynamic monitoring with jointmeters, vibrometers and accelerometers, by Metro C in the period September 2007-November 2009 and they did not highlight criticalities regarding displacements and rotations. It

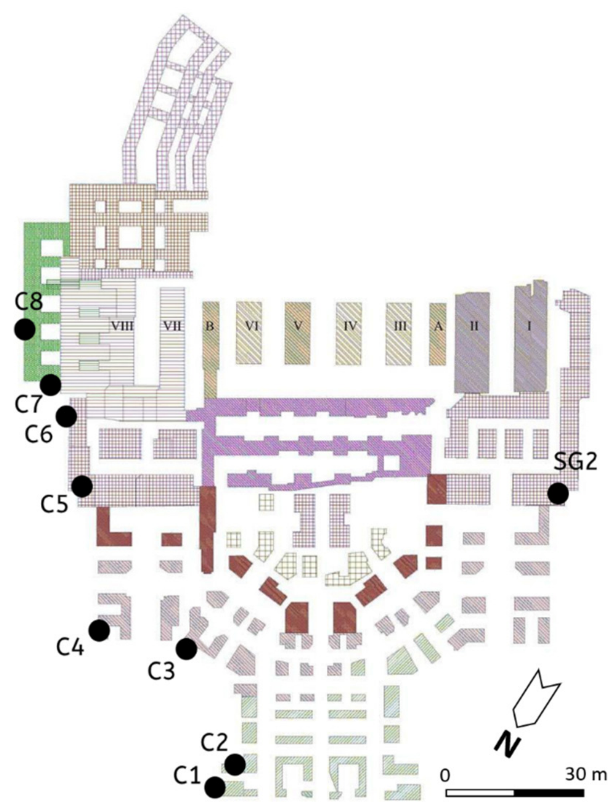

Fig. 5 - Planimetric reconstruction of the Vittoriano foundations (after GIUNTINI, 1954) with location of the Metro C boreholes and pylons number indicated in the text

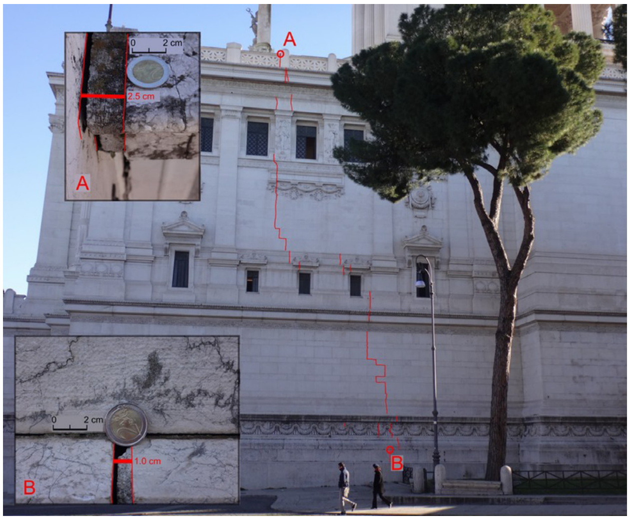

Fig. 6 - Main joints on the western perimeter wall

seems due to cyclical thermal expansions but, more recently, new lesions have been observed on floors and perimeter walls of the right wing. The new cracks (Fig. 6) are few centimetres opened and up to some meters long.

A-DINSAR RESULTS

The results of the large-scale A-DInSAR analyses are reported through maps on orthophotographic bases that show the displacement information.

The validation procedures allowed to obtain about 21,481 reliable measurement points (MP) throughout the survey area for the two orbital geometries. Specifically, in the entire investigation area, over 19,483 MP were obtained from the COSMO-SkyMed ascending and descending data stacks and about 6,465 MP from the ENVISAT ascending and descending data stacks. This difference is due to the different spatial and temporal resolutions of the satellite missions and to the period of acquisition of each satellite mission.

The measurement accuracy for ENVISAT and COSMO-SkyMed datasets were commonly estimated in the order of ±1.5 mm/yr, from literature (ANTONIELLI *et alii*, 2019; BOZZANO *et alii*, 2018). The elaborations carried out with the canonical precision in the observed scenario, which includes the Monument and its surrounding area, show substantial stability (all measurement points have displacement velocities within ±1.5 mm/yr) both in the ENVISAT and COSMO-SkyMed data period.

However, as it can be seen in Fig. 7, the millimetric precision of the measurement is a function of the observed period, of the

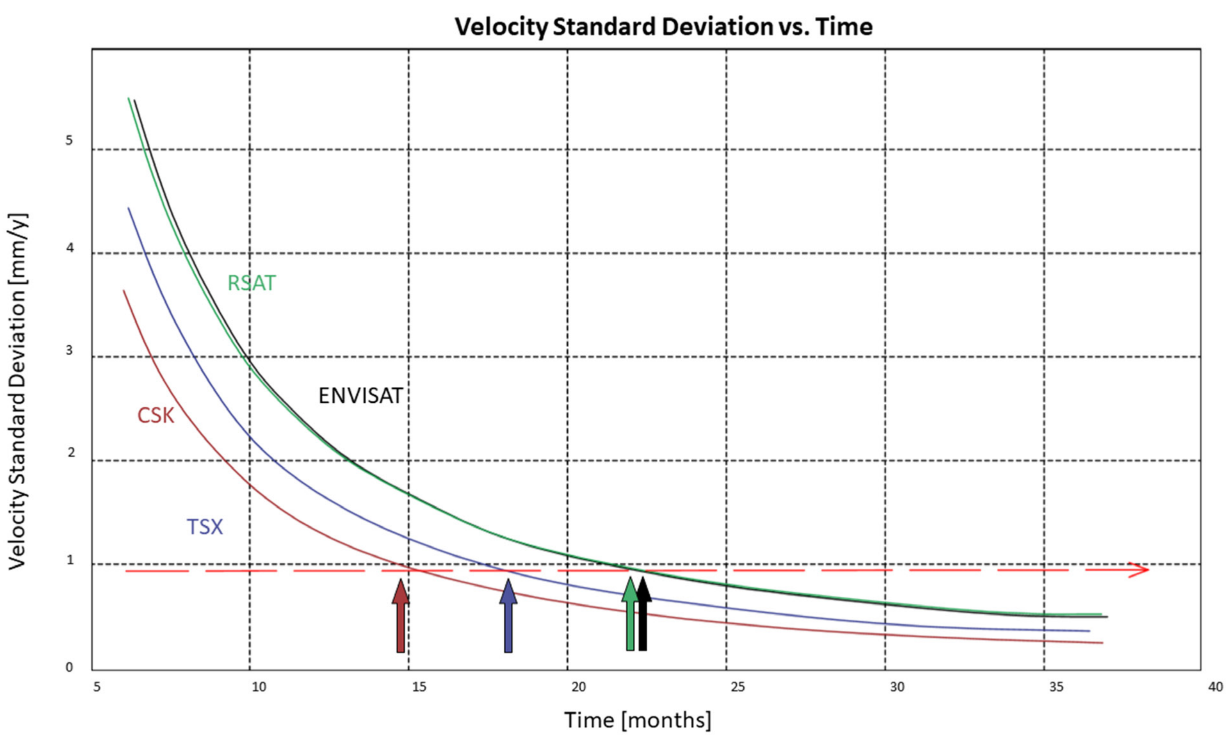

Fig. 7 - Standard deviation of the estimated average displacement rates for different satellites as a function of time for an average atmospheric noise mean square delay (after ROCCA et alii, 2013, modified)

satellite revisit time and of the characteristics of the satellites, in particular the wavelength.

Therefore, thanks to the density and backscattering quality of the natural targets (man-made structures in a densely urbanized area) and to the revisit time length of the period observed through COSMO-SkyMed (about 8 years), it has been possible to extrapolate the maximum information from the obtained results. The scale of PM displacement rates has been reduced, bringing the instrument error to about 0.3 mm/yr.

A colour scale expressed in mm/yr has been adopted to represent the displacement along the Line of Sight (LOS).

The colours from yellow to red, (negative values), indicate points with a deformation rate away from the satellite, while positive values (light blue to dark blue) refer to those points that are moving towards the sensor. The green colour indicates areas with measurement point rates that are not appreciable or not significant (stable point).

By reducing the MP displacement rate scale and indicating measuring points with a displacement rate in the order of +- 0.3 mm/yr in green, it is possible to observe a different scenario. Through the displacement maps obtained through COSMO-SkyMed data, analysed with the new scale of measurement, it can be observed a very different restitution of the recent deformation history in the study area (Fig. 8). The analysis of the scenario of interest leads to the definition of two areas with different deformation trends. These are clearly separated by a line that cuts the scenario in the SW-NE direction. The deformational pattern highlights that the eastern area is affected by slight or negligible movements; in fact it is mainly characterized by MP considered essentially stable, whereas the western area is affected by significant deformations.

By evaluating the data related to the displacement velocity of the MP it can be noticed that:

- in the eastern area (with respect to the SE-NW line) it is identified an almost overall movement trend of ± 0.3 mm/yr indicating a substantial stability;
- the western area shows a higher variability of the displacement values with a velocity peak between -0.3 and -0.6 mm/yr.

Considering both geometries, the histograms in Fig. 8 show that 7733 MP out of 9573 MP (about 81% of the total) have substantial stability. On the other hand, in the western area it is shown that out of 5,443 MP, only 20% are stable. 41% of the total shows a deformation trend between -0.3 and -0.6 mm/yr, while 24% has displacement rates between -0.6 and -0.9 mm/yr.

Within all the observations conducted on the entire scenario, a particular attention was paid to the Vittorio Emanuele II monument. It is evident that this clear asymmetry of deformation behaviour is also identified in the MP relating to the Monument: the eastern and southern portion where MP show an average displacement velocity in the range ± 0.3 mm/yr and the NW

Fig. 8 - A-DInSAR results: Top) Velocity of persistent scatters of COSMO-SkyMed on orthophotographic bases. For every measurement point, it is possible to observe the displacement rate in mm/yr. Negative values (yellow to red) are points with deformation rate in mm/yr. Negative values (yellow to red) are points with deformation rate away from the satellite, while positive values (light blue to dark blue) are points that move towards the sensor. Green points are stable. Bottom) Histograms show the variation of displacement rates in the east and west areas for both acquisition geometries

sector where the MP reveal long-term deformation trends.

By studying the displacement time series of some MP representing the two portions of the monument, it is possible to understand the ongoing process. The time series D, E, F shown in Fig. 9 describe the stability over time of the eastern side of the Monument. The time series A, B and C in Fig. 9 referring to some selected MP on the western side, reveal a difference in the behaviour of the perimeter wall.

The portion of the wall facing Piazza Venezia shows a lowering of the MP which amounts, during the investigated period, to about 5 mm. The time series C, representative of the southern portion of the wall, does not show any deformation trend.

These two different deformation trends straddle an important fracture that crosses the perimeter wall and extends inside the Monument.

DISCUSSIONS AND CONCLUSIONS

The deformation trend involving the historic center of Rome and surrounding areas has been extensively investigated

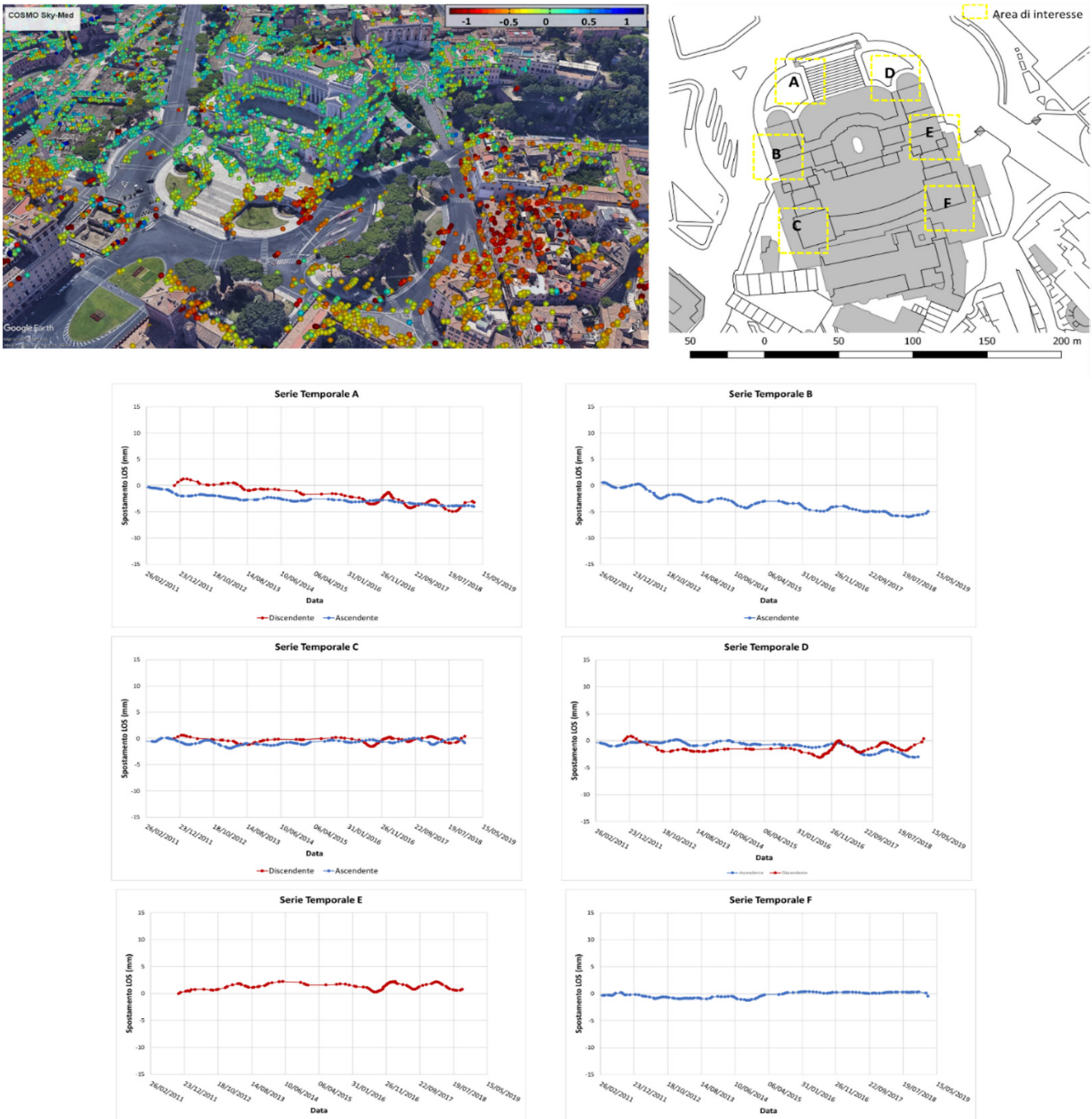

Fig. 9 - Analysis of the MP located on the Vittoriano. Data are related to the analysis performed through COSMO Sky-Med in both geometries (Descending and Ascending). Top: 3D interferometric map and location of the analyzed MP. Bottom: displacement time series representative of the 6 selected areas

in the last few years (e.g. Stramondo *et alii*, 2008; Tapete *et alii*, 2012). In most cases, the recorded MP displacements are ascribed to subsidence or natural/human induced deterioration processes experienced by the archaeological structures and foundations. In particular, the Vittoriano has been the specific subject of InSAR analyses encompassing some sectors of the historic center and single buildings or monuments as well (Zeni *et alii*, 2011; Cigna *et alii*, 2014). Data sets are respectively

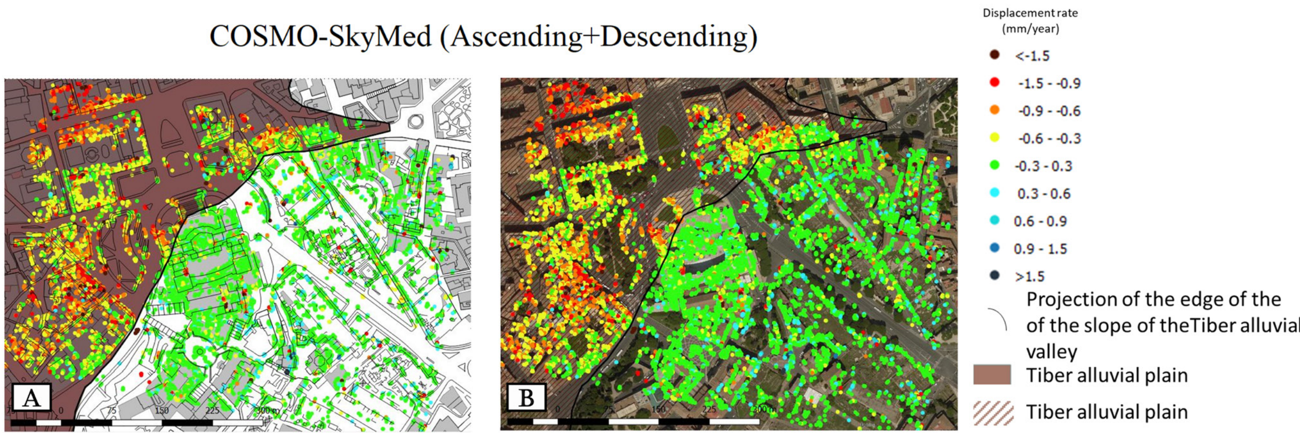

Fig. 10 - Displacement rates according to the line of sight obtained from the images COSMO Sky-Med (2011-2019), ascending and descending mode. The image A is based on the regional CTR and B on an ortho-rectified satellite image

referred to ERS1/2-ENVISAT images spanning the time interval 1992-2010 and Cosmo-SkyMed time series between 2011 and 2013. Results by Cigna *et alii* (2014) pointed out that only some MP over the Sommo Portico show vertical velocities (Vv) ranging between -1mm/yr and -3mm/yr; yet the authors claimed a substantial stability of the Vittoriano, as they did not recognize a clear subsidence pattern. On the contrary, according to Zeni *et alii* (2011), only the NW corner of the Monument shows a subsidence deformation trend with a rate of about -1mm/yr. In both cases no detailed indications about the local subsurface geological conditions are given.

In this paper, the A-DInSAR analysis shows a different behavior in the NW corner of the Monument. In fact, this sector of the Monument is the most affected by displacements; in the time span analyzed, it is shown that the MP tend to move downwards with velocities between 0.3 and 1mm/yr.

The data referring to the geological setting and geotechnical characterization, as well as data related to the urbanization and the foundation types of the Monument were combined to explain the displacement trend obtained through the A-DInSAR analyses.

Through a 3D geological model, it was possible to describe in detail the complex geological arrangement of the study area. In general terms, the geological reconstruction defines complex vertical and lateral lithological variations including a progressive increase in the thickness of the recent Tiber alluvial deposits towards the center of Piazza Venezia where it reaches the maximum thickness.

The model highlights that the NW portion of the Monument rests on soils (Anthropogenic deposits and Tiber alluvial deposits) with poor deformability and shear strength characteristics. According to the A-DInSAR analyses, this part of the Monument coincides with that one subjected to clear downward displacements, pointing out a coherence between the displacement rates and the deformation response of the foundations lithologies (Fig. 10).

The concluding hypothesis is that the NW sector of the Monument is subjected to settlements caused by subsidence of compressible soils, while the remainder of the Monument would not be subject to such displacement. According to this hypothesis, the cracks that appeared recently on the outer western perimeter wall would represent the Monument response to the differential settlements. The causes of the current persistence of subsidence, more than 100 years after its realization, could be the followings:

a. secondary and slow consolidation subsidence induced by the monument load;

b. subsidence induced by local groundwater surface drawdown in recent Tiber alluvial deposits;

c. a combination of the two above mentioned processes.

The final insight of this study is the effectiveness of A-DinSAR techniques in analyzing deformational processes involving large areas and affecting cultural heritage when supported by detailed 3D geological models. This effective combination can be helpful in addressing the adoption of appropriate mitigation measures.

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