Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

SATELLITE RADAR INTERFEROMETRY FOR THE ANALYSIS OF POTENTIAL INSTABILITY IN URBAN AREAS OF HIGH HISTORICAL AND CULTURAL VALUE

Anna PALAMIDESSI[(*)], Silvia BIANCHINI[(*)], Irene CENTAURO[(*)], Veronica TOFANI[(*)], Deodato TAPETE[(**)] & Maria VIRELLI[(**)]

[(*)]University of Florence - Department of Earth Sciences - Firenze (Italy)
[(**)]Italian Space Agency (ASI) - Rome, Italy
Corresponding author: anna.palamidessi@unifi.it

EXTENDED ABSTRACT

Le tecniche di telerilevamento applicate allo studio, tutela e monitoraggio dell'instabilità dei beni culturali risultano oggigiorno una metodologia sempre più utilizzata. In particolare, l'interferometria radar satellitare multitemporale PSI (*Persistent Scatterer Interferometry*) consente lo studio dei movimenti del terreno e dei manufatti, e porta all'identificazione e alla mappatura dei fenomeni deformativi.

L'utilizzo dei dati PSI permette di rilevare le deformazioni del terreno in un ampio intervallo temporale con un'accuratezza millimetrica e senza il contatto con i materiali e le strutture, permettendo così di individuare le aree caratterizzate dai più alti tassi di movimento del terreno, stimare i processi idrogeologici che minacciano il patrimonio culturale e valutare speditivamente le condizioni di stabilità.

La situazione ambientale del territorio italiano potrebbe esporre al rischio idrogeologico anche l'inestimabile patrimonio culturale del paese. Pertanto, nell'ambito del Piano Nazionale Straordinario per il Monitoraggio e la Conservazione dei Beni Culturali è stato definito un accordo tra il Ministero dei Beni Culturali e la Cattedra UNESCO dell'Università di Firenze sulla Prevenzione e Gestione Sostenibile del rischio idrogeologico per attivare il monitoraggio sui Beni Culturali italiani, anche attraverso l'acquisizione e l'elaborazione tramite tecnica PSI di nuovi dati radar satellitari ad apertura sintetica (SAR) con nuove acquisizioni da parte del satellite Cosmo-SkyMed (banda X).

Il presente studio, utilizzando i dati di nuova acquisizione, classifica gli edifici dei siti italiani di valenza storico-culturale di Paestum (SA), Volterra (PI), Orvieto (TR), utilizzando alcuni indici come l'indice di copertura dei dati in ogni edificio (Id) e l'indice di velocità media dei dati PS in ogni edificio e nel suo intorno (Ivmean). Questi indici, rappresentati con classi di colori diversificati in base al valore calcolato, consentono un'analisi dettagliata e chiara dei tassi di velocità dell'edificato su scala locale. La procedura sviluppata è stata testata su dataset PSI precedenti, tenendo conto delle specificità del sensore radar e della risoluzione spaziale delle immagini SAR. Tale indagine preliminare non è finalizzata all'individuazione di processi deformativi del terreno, ma nel caso di aree urbanizzate permette un veloce screening per individuare edifici soggetti a movimenti, nei quali potrebbe venire compromesso lo stato di conservazione.

Il telerilevamento radar satellitare emerge come uno strumento strategico e operativo per il monitoraggio e la protezione del patrimonio culturale, offrendo un approccio efficace alle deformazioni del terreno e ai rischi geologici. Fornisce inoltre una base solida per una valutazione approfondita delle condizioni e la pianificazione di interventi necessari.

ABSTRACT

Satellite radar remote sensing techniques are non-invasive methodologies that can be effectively used for diagnostic purposes, measuring displacements, and monitoring cultural assets, architectural structures, and archaeological areas without injuring their integrity.

The environmental condition and hydrogeological hazard in the Italian territory could make its invaluable Cultural Heritage at risk. Therefore, within the National Extraordinary Plan for Monitoring and Conservation of Cultural Heritage, an agreement has been established between the Ministry of Culture and the UNESCO Chair of the UNiversity of Florence on Prevention and Sustainable Management of Geo-hydrological Hazard to analyse ground motion rates on built-up areas by means of acquisition and PSI (Persistent Scatterers Interferometry) elaboration of high-resolution Cosmo-SkyMed synthetic aperture radar (SAR) satellite data (X-band).

This technique can provide useful support on the conservation and protection of Cultural Heritage, as it endorses an innovative perspective on the condition and safety of historical sites, monuments, archaeological sites and artworks, thus contributing significantly to their preservation over time. Through SAR interferometric techniques, it is possible to identify millimetric displacements related to environmental threats, such as slow-moving landslides.

This work proposes the classification of buildings of urban areas by using two indices based on PSI data coverage and deformation rates: the data coverage index in each building (Id) and the average velocity index of PSI data in each building and its surroundings (Ivmean), representing deformation rates in a locally scaled, easily understandable color-coded format.

This method has already been tested in scientific literature on other SAR datasets for evaluating instability at the building scale. The approach aims to develop a fast and low-cost system to assess buildings that are potentially exposed to deformation and therefore more susceptible to damage in heavily urbanized areas with high historical-cultural value. In order to safeguard Cultural Heritage from natural disasters, the proposed methodology integrates a high degree of scientific and technological expertise and presents an updated and accurate screening of potential deformations due to hydrogeological hazards.

Keywords: hydrogeological hazards, remote sensing, cultural heritage, satellite radar interferometry, buildings velocity, instability in urban areas.

INTRODUCTION

Within the framework of the Extraordinary Plan for Monitoring and Conservation of Immovable Cultural Heritage, a national program funded by the Italian Ministry of Culture (MiC) aimed at the conservation of Cultural Heritage, especially urban assets, and their structural safety concerning various natural and anthropogenic hazards, the UNESCO Chair "Prevention and Sustainable Management of Hydrogeological Risk" established at the University of Florence is conducting an analysis on some Italian sites of high historical and cultural value by using deformation measurements obtained from high-resolution radar satellite SAR (Synthetic Aperture Radar) images from COSMO-SkyMed constellation in X band managed by the Italian Space Agency (ASI). These measurements are combined with geothematic and on-site terrestrial survey data.

This work presents some results related to the mapping and analysis of deformations at the scale of individual buildings on the sites of Paestum (SA), Orvieto (TR) and Volterra (PI) in Italy to evaluate potential movements of the structures in relation to the geomorphological context of the area.

The results of this work demonstrate how satellite radar remote sensing techniques, particularly high-resolution COSMO-SkyMed data, can support and enhance multidisciplinary knowledge framework for geohazard management in urban areas with Cultural Heritage.

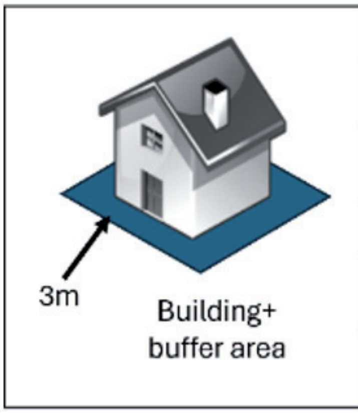
MATERIALS AND METHODS

The Synthetic Aperture Radar (SAR) satellite images acquired by the COSMO-SkyMed (CSK) constellation have been processed using the Persistent Scatterers Interferometry (PSI) technique.

PSI technique is capable of measuring displacements with millimeter precision, dense spatial sampling, wide area coverage and systematic temporal updating. The basic principle relies on the detection of stable radar targets within SAR images, the so-called Persistent Scatterers (PS), which correspond to anthropic or natural objects characterized by a stable phase signal (Ferretti *et alii*, 2001). The PSI approach allows measuring the movements of each PS along the satellite line of sight (LOS) with respect to an assumed stable reference point and it is particularly suitable in urban areas, where many potential coherent PS such as buildings and road can be retrieved. In this work the SqueeSAR algorithm, which measures ground displacements using both PS and the distributed scatterers (DS), generally referred as PSI data hereafter, has been exploited for processing COSMO-SkyMed images (Ferretti *et alii*, 2011). The methodological procedure in this study involves managing the displacement measurements of PSI data along with thematic and cartographic data, geological and geomorphological information, topographic and geological maps, recent orthophotos, an inventory of landslides, and building typologies (Bianchini *et alii* 2012).

In building surveying, the assessment of building conditions is typically provided as an index based on numbered classes to express the structural conservation status, offering a concise and schematic output (Salim & Zahari, 2011; Pratesi *et alii*, 2015; Wahida *et alii*, 2012).

In this study, we adopt a methodological procedure already proposed and tested in scientific literature (Pratesi *et alii*, 2015; Bianchini & Festa, 2022) based on Persistent Scatterers



PS COVERAGE (Asc + Desc)						
PS number in building	No data	≤2	≤4	≤6	≤10	>10
Index (**Id**)	ND	E	D	C	B	A
Mean or Max Velocity (mm/year)						
|V mean| or |V max| mm/year	No data	≤2,0	2,0-3,0	3,0-5,0	5,0-10,0	>10
Index (**Ivmean**) or (**Ivmax**)	ND	E	D	C	B	A

Fig. 1 - The proposed set of indices for classifying PSI data and assessing the deformation conditions of buildings at a local scale, on the left a schematic diagram representing a building within a buffer area

Interferometry (PSI) analysis for assessing potential instability at the building scale using classification indices. This involves combining observations and measurements in both ascending and descending geometries related to the same building and its 3-meter buffer area (a value chosen based on the spatial resolution of the COSMO-SkyMed satellite data), considering the absolute values of velocities (combined deformation values with negative and positive signs, representing movements away from and toward the satellite sensor from ascending and descending orbits.). The boundaries of building buffers were intersected with PSI data falling within these areas, and values were divided into 5 classes and subsequently into 5 indices. This reduction is feasible when PSI coverage on the structure is sufficient.

Two indices, namely the data coverage index of each building (Id) and the average velocity index of PS data for each building and its surroundings (Ivmean) are considered: thresholds and ranges were set according to values already tested in scientific literature in similar urban settings (Bianchini & Festa, 2022). These indices combined with in situ field analysis can help in prioritizing attention and in identifying most critical built-up areas affected by highest ground motion rates, potentially related to instabilities due to hydrogeological hazards.

The approach based on indices is shown in Figure 1, and illustrates the proposed set of indices for classifying PSI data and evaluating deformative conditions of buildings at the local scale.

For each structure, PSI coverage and deformation rates are translated into classification indices. Specifically, a PSI coverage index (Id) was defined to express the spatial distribution of PSI data falling within the building and its buffer area. This index ranges from E to A, indicating poor to optimal PSI coverage on a single building.

The average velocity indices were defined based on the mean velocity values of PSI within the building buffer. The velocity index ranges from E to A, coded with colours from green to red (indicating "stable structure" to "critical velocity"). Class values are scaled based on the Line-of-Sight Velocity (VLOS) of PSI (mm/year).

The No Data (ND) class for each index refers to buildings where no PS were identified within the boundaries of the buffer area.

The thresholds chosen for the velocity classes take into account the standard deviation of the data and the thresholds of movement that can cause damage to the urban built environment. These velocity thresholds are based on the work of Mansour *et alii* (2011), which identifies a velocity of more than 5 mm/year as a cause of damage to the urban fabric. It shows that residential buildings can tolerate higher sliding velocities and total displacements than the other facilities before suffering serious damage. The extent of the damage will worsen if appropriate measures are not taken in time to prevent the accumulation of movement. Finally, the satellite data are validated by in-situ evidence and cross-comparisons.

RESULTS AND DISCUSSION

The case of Paestum in Campania region

Paestum is an archaeological site located south-east of the Gulf of Salerno, in the southern part of the Sele Valley in the province of Salerno. The site includes Doric-style temples, unique examples of Magna Graecia architecture, and a Greek city wall, reinforced in Lucanian and then Roman times, almost entirely preserved (Cozzolino *et alii*, 2019). Paestum is in a flat area and it has a bedrock on travertine interspersed with clayey silt and sand. The archaeological park of Paestum, together with the archaeological sites of Velia and the Certosa di Padula are included in the National Park of Cilento and Vallo di Diano registered in the WHL since 1998 (inclusion criteria *iii* and *iv*).

In the archaeological area of Paestum there are few buildings, some historical, others recent (such as the museum, restaurant and other service structure). The archaeological area has a good

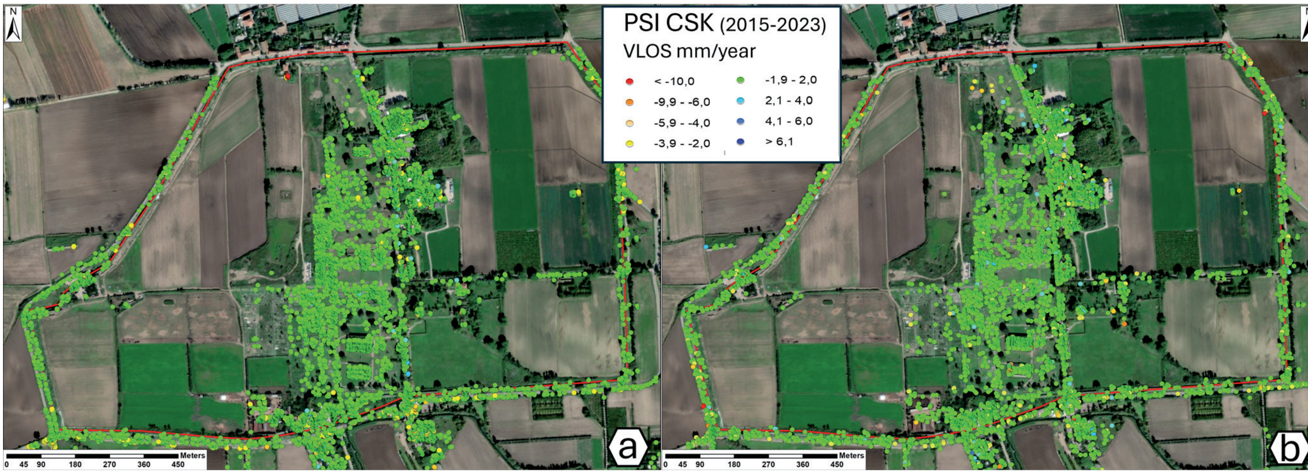


Fig. 2 - The new COSMO-SkyMed dataset in Paestum. a) Ascending dataset. b) Descending dataset

Fig. 3 - a) Data coverage on building, in grey the buildings that have no data coverage, in violet buildings that have more than 10 PS in the roof or in their buffer area. b) Map of Ivmean Index in Paestum

coverage of PSI data as show in Figure 2, most of PS appear green in colour and therefore have average velocity values within the range chosen as the stability threshold COSMO-SkyMed data and the elaboration of velocity on buildings. The average on velocity shows in Figure 4a has only one small building in class D, the other 90 are in class E.

Considering that a velocity of more than 5 mm/year is a cause of damage to urban buildings (Mansour *et alii*, 2011), we can therefore evaluate the archaeological site of Paestum as not affected by a displacement that could cause damage to existing structures.

The case of Orvieto in Umbria region

Orvieto is located in the south-western sector of Umbria, in the province of Terni at an altitude of about 300 m a.s.l. on a tuff cliff 50-meters-thick (ignimbrite of Orvieto - Bagnoregio) bordered by subvertical cliffs overlooking the valley of the Paglia river, a right tributary of the Tiber river. This tuffaceous mesa overlies the over-consolidated clay formation; between the tuff and the clay substrate lies a fluvio-lacustrine unit (thickness varying from 3-15 metres). (Tommasi *et alii*, 2006). Orvieto has been included in the UNESCO Tentative List since 2006 (inclusion criteria *i*, *iv*, *v*) and in 2018 joined, along with seven other Italian Etruscan cities (Arezzo, Volterra, Populonia, Perugia, Veio, Tarquinia, Marzabotto), the unified World Heritage nomination project called the Spur project (an Etruscan term meaning city) that focuses on the essence of the Etruscan city understood in its architectural and urban aspects. The Orvieto city has most of PS that appear green in colour and therefore have average velocity values within the range chosen as the stability threshold COSMO-SkyMed data as shown in Figure 4. The velocity of 714 buildings has been analysed. Among these, 31 are not covered by data and are located in a peripheral position and they appear in grey colour in all the maps. The map of average on velocity (Ivmean) shows in Figure

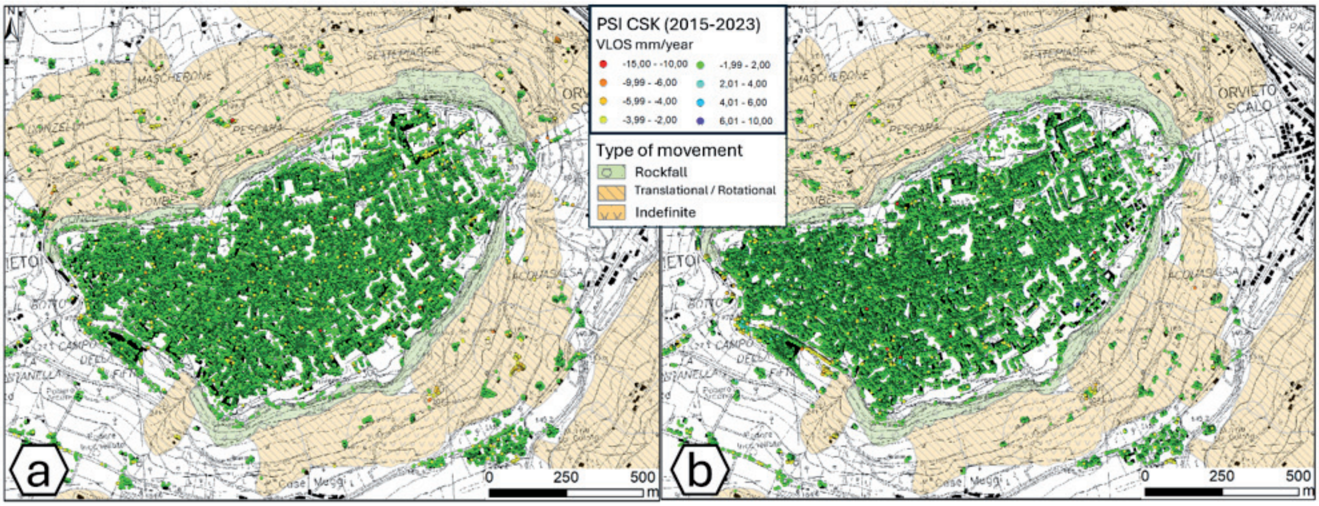


Fig. 4 - The new COSMO-SkyMed dataset in Orvieto overlapped on Landslide Inventory from IFFI (ISPRA). a) Ascending dataset. b) Descending dataset

Fig. 5 - Data coverage on building overlapped on Landslide Inventory from IFFI (ISPRA), in grey the buildings that have no data coverage, in violet buildings that have more than 10 PS in the roof or in their buffer area, in dark blue have 7 or more PS in the roof or in their buffer area. b) Map of Ivmean index in Orvieto

5b are 675 buildings in class E, in light green colour; 6 in class D in Dark green colour; 2 are in class C in yellow colour; there are no buildings in class B and A.

Considering that a velocity of more than 5 mm/year is a cause of damage to urban buildings (Mansour *et alii*, 2011), we can therefore assess the Orvieto city centre as not being affected by slow displacement that could cause damage to existing structures.

The Case of Volterra in Tuscany Region

Volterra in Tuscany Region is one of the most important Etruscan settlements, which then developed as a Roman centre and later as a medieval city. The Volterra city center is located on a morphological tableland, surrounded by sub-vertical walls (Sabelli *et alii*, 2012). The morphology of the area is mainly due to the evolution of the sedimentary sequence consisting of a base of Blue clay, overlain by sands and a layer of limestone, known in literature as the Calcari di Volterra, on which the oldest part of the built-up area is built. The tabular relief on which the historic centre of the town is located and the presence of the well-known 'Balze' (crags) are due to the undermining of the clays at the base of the overlying sandstones and limestones, generating frequent rockfalls and retreat of the sub-vertical walls. The town retains an Etruscan historical centre and medieval buildings of considerable historical and architectural interest. Volterra has been included, as a historical city and cultural landscape, in the UNESCO Tentative List since 2006 (as Orvieto). In the city centre of Volterra there are a very good coverage data as shown in Figure 6 and in Figure 7 we can see that the city centre appears quite stable by COSMO-SkyMed data and the elaboration of velocity on buildings.

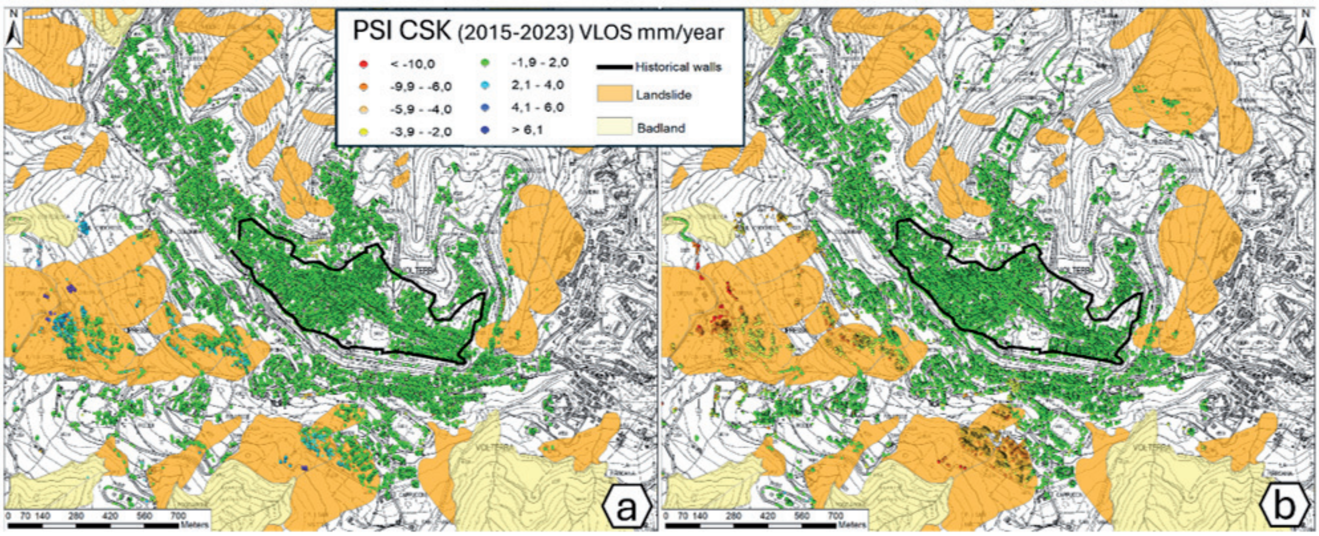


Fig. 6 - The new COSMO-SkyMed dataset in Volterra overlapped on Landslide Inventory from IFFI (ISPRA). a) Ascending dataset. b) Descending dataset

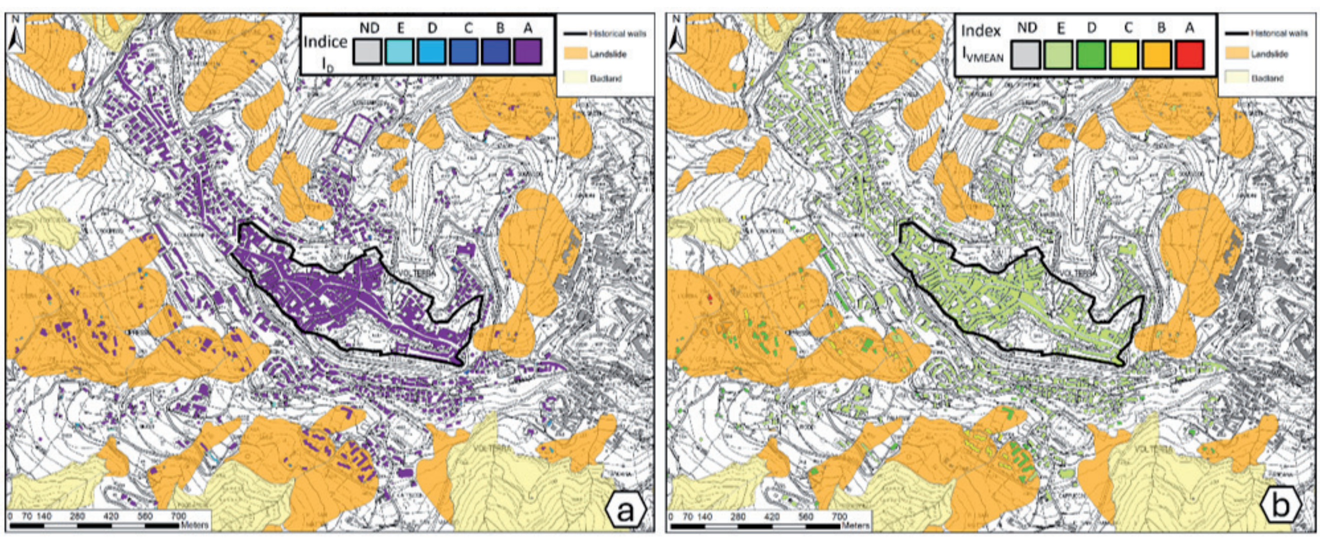


Fig. 7 - Building data overlapped on Landslide Inventory from IFFI (ISPRA). a) Data coverage on building, in grey the buildings that have no data coverage, in violet buildings that have more than 10 PS in the roof or in their buffer area. b) Map of Ivmean index in Volterra

In Volterra 1088 buildings were examined; between these 269 have no data coverage and they appear in grey colour in all the maps. The average on velocity (Ivmean, Figure 7b) are 693 buildings in class E, in light green colour; 76 in class D in Dark green colour; 31 are in class C in yellow colour; 15 are in class B and 2 are in class A. In the map, the buildings displayed with red, orange, and yellow are located on landslide bodies mapped in the IFFI inventory.

All the urban fabric of the city centre is shown in green colour, since the velocity is less than 2 mm/year.

DATA VALIDATION

The data from the three sites of Paestum, Orvieto and Volterra show buildings in green colour in the archaeological area and in Old Town on the map of average velocity on building, so the Cultural Heritage of this city has a velocity of less than 2 mm/year, we can therefore consider that the Cultural Heritage is not affected by slow displacement that could cause damage to existing structures.

It should be emphasised that only the satellite radar data from the Volterra site have been validated by in-situ evidence and cross-comparison. In situ surveys have confirmed deformations on buildings that exhibited greater movements in the data analyses. These buildings are situated within landslide bodies that had been previously mapped.

The *in-situ* campaign of the buildings shows that the ones that are in critical classes in the velocity index maps (coloured in orange and red) have damage to the structures, as can be seen in Figure 8.

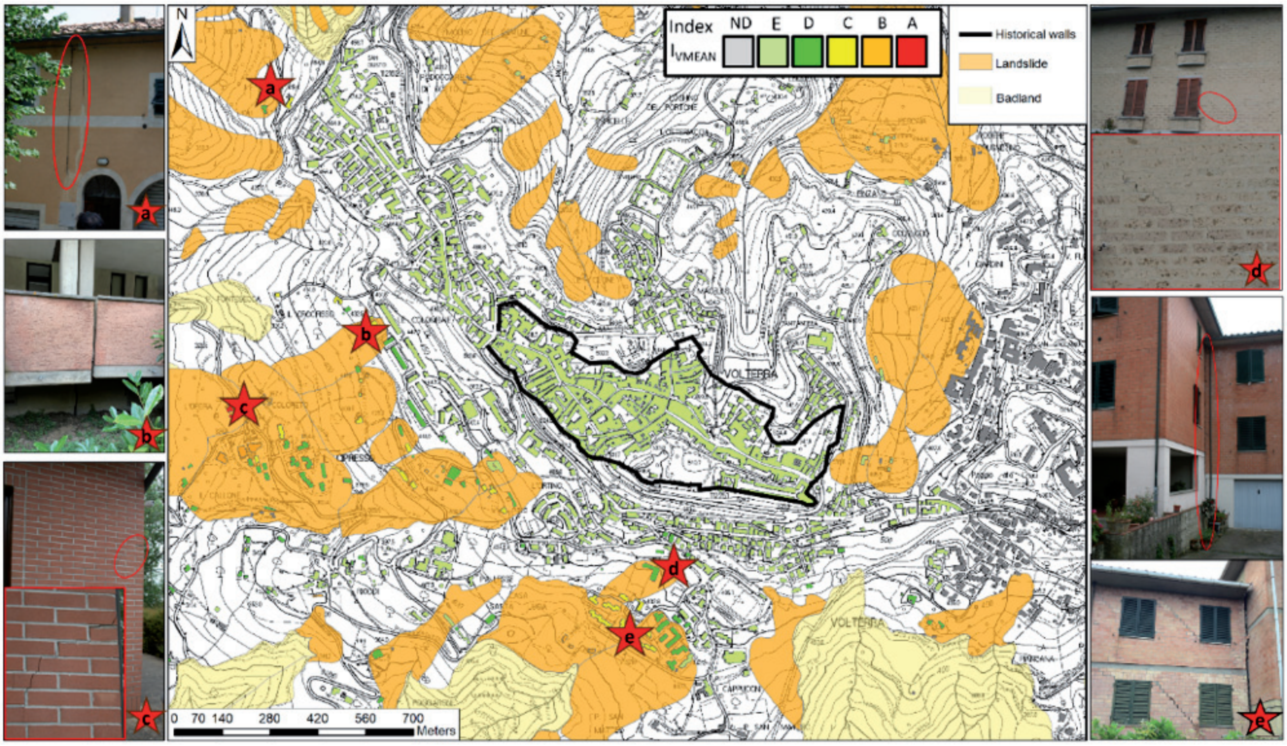


Fig. 8 - Map of Ivmean index in Volterra, with the red star, the areas where the photos were taken

It is important to remember that terrain deformations recorded by PSI data detected on rocks, soil, and natural and artificial elements can reasonably be attributed to ongoing movements. On the other hand, the PSI displacements measured on buildings can result from more complex processes, such as soil-structure interaction, but also from the type of building and construction materials. Therefore, the recorded displacement and potential damage may result from these multiple factors and their mutual interaction.

CONCLUSIONS

The use of satellite radar data for Earth Observation can facilitate the mapping and monitoring of ground movements that may impact the Cultural Heritage and urban fabric, posing threats to their integrity and stability. Satellite remote sensing techniques prove to be effective tools for this purpose, given the necessity to employ non-invasive approaches without direct contact with the objects of study to prevent damage. In this context, the exploitation of multitemporal COSMO-SkyMED interferometric radar satellite data provides millimetric measurements of ground displacement, enabling periodic analysis of ground deformations, particularly in urban areas.

Specifically, Persistent Scatterer Interferometry (PSI) data derived from systematic satellite acquisitions and processing of SAR imagery can scan the territory and rapidly highlight areas characterized by higher ground deformation rates and identify historical and Cultural Heritage sites prone to geomorphological hazard or undergoing other deformation processes.

In this study, the buildings of the urban fabric were classified based on data coverage indices and average velocities of PSI data assigned to structures at the local scale. For each building, PS coverage and PSI deformation rates were converted into two classification indices: Id (Data Coverage Index) and Ivmean (Average Velocity Index).

The methodological procedure for calculating these classification indices has been previously tested on other PSI datasets of medium-resolution SAR (Synthetic Aperture Radar) images (Bianchini & Festa, 2022; Pratesi et alii, 2015). It should be emphasized that in the proposed procedures, the choice of the buffer area around buildings and the speed index classes must take into account the radar sensor used and the spatial resolution of the SAR images.

The building velocity assessment proposed in this study can optimise the use of PSI datasets in terms of spatial distribution and velocity information at the artefact scale, providing a rapid and practical method for the early identification of buildings that may be damaged by displacement. Deformation rates are translated into colour-coded outputs in easily identifiable classes for surveyors and end-users responsible for environmental, urban planning and heritage protection.

In conclusion, this procedure, based on PSI remote sensing data and applied to the architectural heritage in urban contexts, serves as a strategic and operational tool for monitoring and safeguarding Cultural Heritage sites. It also provides a valuable opportunity to incorporate effective characterization of ground deformation rates and geological hazards into hydrogeological risk assessments of cultural heritage assets, with the aim of assessing structural condition and better planning interventions.

REFERENCES

Bianchini S., Cigna F., Righini G., Proietti C. & Casagli N. (2012) - *Landslide HotSpot Mapping by means of Persistent Scatterer Interferometry*. Environmental Earth Sciences, **67**(4): 1155-1172.

Bianchini S. & Festa D. (2022) - *Satellite Radar Interferometry for Monitoring Historic Urban Fabric: Lucca and Florence Test Cities.* The Future of Heritage Science and Technologies, **3**: 31-46.

Cozzolino M., Longo F., Pizzano N., Rizzo M.L., Voza O. & Amato V. (2019) - *A Multidisciplinary Approach to the Study of the Temple of Athena in Poseidonia-Paestum (Southern Italy): New Geomorphological, Geophysical and Archaeological Data*. Geosciences **9**(8): 324. https://doi.org/10.3390/geosciences9080324

Ferretti A., Prati C. & Rocca F. (2001) - *Permanent scatterers InSAR interferometry.* IEEE Trans. Geosci. Remote Sens., **39**: 8-20.

Ferretti A., Fumagalli A., Novali F., Prati C., Rocca F. & Rucci A. (2011) - *A new algorithm for processing interferometric datastacks: SqueeSAR™*'. IEEE Trans. Geosci. Remote Sens., **49**: 3460-3470.

ISPRA - The IFFI project (2007) – *Inventario dei Fenomeni Franosi in Italia (Italian landslide inventory)*. https://www.progettoiffi.isprambiente.it/

Mansour M.F., Morgenstern N.R. & Martin C.D. (2011) - *Expected damage from displacement of slow-moving slides*. Landslides, **8**: 117-131. https://doi.org/10.1007/s10346-010-0227-7

Pratesi F., Tapete D., Terenzi G., Del Ventisette C. & Moretti S. (2015) - *Rating health and stability of engineering structures via classification indexes of InSAR Persistent Scatterers.* Int. J. Appl. Earth. Obs. Geoinf., **40**: 81-90.

Sabelli R., Cecchi G. & Esposito A.M. (2012) - *Mura etrusche di Volterra. Conservazione e Valorizzazione*; Bientina, Ita.: La Grafica Pisana, Italy.

Salim N. A. A. & Zahari N. F. (2011) - *Developing integrated building indicator system (IBIS) (a method of formulating the building condition rating).* Procedia Eng, **20**: 256-261.

Tommasi P., Pellegrini D., Boldini D. & Ribacchi R. (2006) - *Influence of rainfall regime on hydraulic conditions and movement rates in the overconsolidated clayey slope of the Orvieto hill (central Italy)* Canadian Geotechnical Journal., **43**(1): 70-86

Wahida R. N., Milton G., Hamadan N., Lah N. & Mohammed A. H. (2012) - *Building condition assessment imperative and process*. Procedia-Soc Behav Sci., **65**: 775-780

Received January 2024 - Accepted April 2024