THE MONITORING OF URBAN ENVIRONMENTS AND BUILT-UP STRUCTURES IN A SEISMIC AREA: WEB-BASED GIS MAPPING AND 3D VISUALIZATION TOOLS FOR THE ASSESSMENT OF URBAN RESOURCES

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ABSTRACT

In this paper, a non-invasive infrastructural system called MASSIMO is presented for the monitoring and the seismic vulnerability mitigation of cultural heritages. It integrates ground-based, airborne and space-borne remote sensing tools with geophysical and *in situ* surveys to provide a multi-spatial (regional, urban and building scales) and multi-temporal (long-term, short-term and near-real-time scales) monitoring of test areas and buildings. The measurements are integrated through web-based Geographic Information System (GIS) and 3-dimensional visual platforms to support decision-making stakeholders involved in urban and structural requalification planning. An application of this system is presented over the Calabria region for the town of Cosenza and a test historical complex.

1. INTRODUCTION

The monitoring of urban landscape and buildings for risk mitigation purposes is a challenging task that concerns two operational issues [1]. On the one hand, there is the complexity in managing and assimilating huge quantity of reliable measurements able to monitor anthropogenic and natural phenomena, which may impact on urban environment, buildings and human lives. On the other hand, there is the on-going difficulty to provide user-friendly results easily understandable and manageable by end-users that are involved in environmental and structural monitoring. Both issues are relevant in case of natural hazards, where time-continuous multi-temporal and multi-spatial information is needed for the effective safeguarding of landscapes, structures and human lives. In this framework, the assimilation of remote sensing data with geophysical and in situ survey could represent a suitable approach for the multi-risk mitigation of urban assets [2].

In this work, an infrastructural system for the seismic monitoring of urban environments and structures is presented. Based on the combined use of remote sensing sensors, geophysical investigations and in situ measurements, the conceived methodology consists of three modular interconnected steps (see Fig. 1).

In the first step, seismogenic analysis are used together with space-borne and airborne remote sensing tools for the long-term monitoring of hazardous prone areas at regional scale. Within such a framework, airborne aeromagnetic surveys are used to improve the knowledge about seismogenic structures, providing physical and geometric properties of detected fault systems. The latter are used with geophysical investigation of the area to simulate different deterministic shaking scenarios of the area. These investigations are further integrated with both surface deformation and land-cover mapping analyses. The former is provided through the interferometric processing of COSMO-SkyMed Synthetic Aperture

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Radar (SAR) measurements. The latter is obtained through the supervised classification of space-borne Geoeye-1 multispectral imagery.

In the second step, geological setting and geotechnical surveys of the area are jointly exploited with airborne and ground-based remote sensing sensors to provide the short-term monitoring of urban areas at basin scale. Within such a framework, the evaluation of seismic site effects is accomplished to describe the response of the soil with respect to the simulated earthquakes. These investigations are then complemented with: (i) airborne Light Detection And Ranging (LiDAR) measurements for providing the digital terrain & surface models of the area; (ii) high-resolution land cover mapping through the spectral-based classification of airborne hyperspectral data; (iii) the surface displacement analysis through the interferometric processing of Ground-based (GB) SAR measurements.

Finally, the third step consists in combining proximal remote sensing tools for the near-real-time monitoring of buildings in terms of structural, geometrical and material properties. Within such a framework, a terrestrial laser scanner (TLS) is used to provide the 3-dimensional (3D) modeling of buildings. Moreover, noise measurements inside building and interferometric Real Aperture Radar (RAR) data are used to assess the vibrating properties of the observed structure. All these surveys are then integrated with non-destructive testing techniques (e.g. infrared thermal camera, flat jacks testing, crack pattern analysis, etc.) to monitor the main structural and material properties of the buildings.

The products provided by each investigation step are assimilated and displayed as geo-spatial metadata in a dedicated web-based Geographic Information System (GIS) and a 3D visual platform. Both value-added products could be very useful to support decision-making policy, risk mitigation plans and restoration activities. Some meaningful results of the proposed approach are shown to monitor cultural heritages within the seismic area of Calabria Region.

The paper is organized as follows. In section 2 the theoretical background of each adopted sensor and technique is briefly outlined. In sections 3 some experimental results are presented and discussed. In section 4 the value-added products of the proposed methodology are described. In section 5 concluding remarks are outlined.

2. THEORETICAL BACKGROUND

The methodology, which is proposed and implemented for the seismic monitoring of historic heritages and urban environments, relies on a multi-spatial and multi-temporal approach: the regional-scale and long-term analysis, the urban-scale and short-term analysis, the building-scale and near-real-time analysis (see Fig. 1). The regional-scale analysis of the seismic environment (from hundreds to tens km^2) is provided to monitor long-term (annual scale) surface and sub-surface phenomena that may impact on selected urban areas and buildings. The urban-scale analysis of the urban landscape (from tens km^2 to hundred m^2 scale) is provided to monitor and assess short-term (monthly scale) processes and phenomena, which may impact on selected historic structures. The building-scale analysis is concerned to provide the near-real-time monitoring about the conservation status of historic buildings.

In the following subsections, the techniques and the sensors adopted to implement the conceived methodology are briefly described.

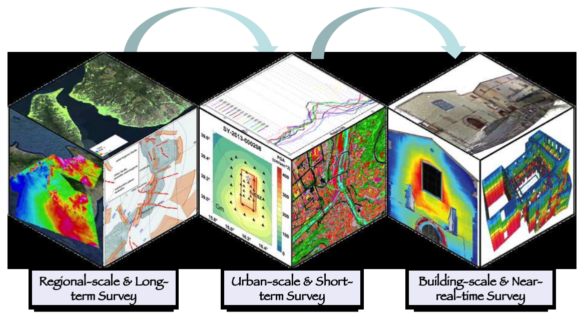


Fig. 1. Block scheme of the proposed methodology.

2.1 Regional-scale & Long-term analysis

The regional-scale (from hundred to tens tens km^2 scale) & long-term (annual scale) analysis aims at describing the regional seismic activity together with the sub-surface fault systems, surface deformation processes and land use mapping of the area. To this purpose, it conceives the analysis of seismogenic sources combined with airborne magnetic surveys, space-borne SAR and Optical sensors, respectively.

Referring to the seismogenic sources analysis, the identification of possible active seismogenic structures together with the evaluation of seismic effects across crustal materials represent non-trivial issues for environmental and building safeguarding purposes. In this framework, a set of activities has been foreseen with the objective to: (i) improve the instrumental monitoring of the regional seismicity, to gather a better characterization of seismic sources together with crustal geometries and structures; (ii) characterize seismogenic structures through aeromagnetic surveys; (iii) simulate deterministic shaking scenarios to study the seismic response of monitored structures.

Firstly, new seismic stations have been deployed and installed on the whole Calabria region for improving the instrumental seismicity and describing the geological structures with relevant geo-mechanical features.

Secondly, magnetic surveys have been performed through high-resolution airborne sensors. They represent a powerful tool able to provide a detailed picture of crustal settings and highlight previously unrecognized upper crust fault geometry [3]-[4]. The key sensor is an airborne magnetometer, which is able to measure the spatial changes of Earth's magnetic field associated to crustal phenomena. The expected output is the map describing the magnetic anomalies of crustal rocks that are associated to seismic tectonic structures.

Thirdly, the faults identified by the Database of Individual Seismogenic Sources (DISS) [5] and properly characterized through aeromagnetic surveys have been used as basic input to simulate deterministic shaking scenarios for different classes of magnitudes. In detail the Deterministic Stochastic Method [6] has been used to provide a wide dataset of synthetic waveforms, each one representing a specific shaking scenario expected at the bedrock for the interested area.

Following the analysis of seismogenic sources, the monitoring of surface deformations and the land use mapping have been performed in dense urban areas to ensure the more effective management and prediction of multi-hazards risk. On the one hand, measuring surface deformations allow assessing and monitoring the main causes of ground displacement in view of multi-risk mitigation plans [7]. On the other hand, land mapping analysis allows determining the current land use, planning efficient land management practices, monitoring changes in urban areas, as well as identifying critical infrastructures and network facilities [8]. As a result, in this work surface deformation phenomena and the land cover mapping have been analyzed on both regional- and long-term scales using space-borne multi-temporal SAR analysis and airborne hyperspectral images, respectively. In detail, X-band COSMO-SkyMed© SAR data have been collected and processed through a Differential Interferometric SAR (DInSAR) technique based on the Small Baseline Subsets (SBAS) approach for surface displacement analysis [9]. Expected outcomes are georeferenced mean surface deformation velocity maps (in mm/yr) and time series of ground displacements (in mm). The analysis of land use and coverage has been achieved by processing IMSpectorV10E acquisitions of the airborne IPERGEO© sensor through the Spectral Angle Mapper (SAM) classification technique [10]. Expected outcomes are georeferenced, supervised land-use classification maps of observed scenarios**.**

2.2 Urban-scale & Short-term analysis

The local-scale (from tens km^2 to hundred m^2 scale) and short-term (monthly scale) analysis aims at monitoring and assessing short-term processes and phenomena in urban areas, which may impact on selected historic structures. To this purpose, geological and geotechnical surveys of the area have been integrated with airborne LiDAR analysis to describe the site seismic response, the surface geology, the topographic profile and the features of built-up areas.

The site seismic response analysis is a key factor to study the seismic response of an earthquake-prone area, as well as to better characterize the amount of ground shaking and soil-structure interaction [11]. As a result, in this work, the geophysical/geotechnical properties of the subsoil have been identified by means of ambient noise measurements performed at single station. The expected output is the spectral ratio between horizontal and vertical components of the ambient vibrations (HV), measured at the same point.

Following the site-seismic response analysis, the survey about topographic and built-up properties is conceived for evaluating the seismic vulnerability of urban environments [12]. On the one hand, the topographic analysis about seismic areas allows describing the terrain and surface properties with the mapping of areas prone to natural and/or anthropogenic disasters (e.g. earthquakes, landslides, subsidence). On the other hand, the knowledge about built-up areas is useful for discriminating urbanized areas with respect to rural and vegetated fields, as well as for updating land registers in urban and risk mitigation plans. As a result, in this work, an airborne LiDAR measurement campaign has been carried out with the RIEGL LMS-Q680i© sensor, to achieve the characterization of the urban test area in terms of topographic and built-up areas information. Expected outputs are the Digital Terrain Model (DTM), Digital Surface Model (DSM) and the geo-referenced map of building footprints with geometrical information (e.g. height, area, perimeter and volume of structures).

2.3 Building-scale & Near-real-time analysis

The building-scale & near-real-time (hourly scale) analysis is concerned to provide a near-real-time monitoring about the conservation status of building. To this purpose, the analysis of geometric, structural, material and vibrating building properties has been provided through proximal remotely sensing tools.

The geometrical and structural reconstruction of buildings represents a key step oriented to the reconstruction of the interested volume as well as the identification of main bearing structures and building properties, crack pattern investigations and numerical modeling [13]. To this purpose, geometrical and structural analyses of historic buildings have been carried out through TLS surveys, performed by the Z+F® Imager 5010c sensor. Expected outputs are 3D building modeling and 2D morphological maps evaluated with respect to fitting planes.

The analysis about the material properties of a built structure is fundamental to evaluate its conservation status, together with its construction properties and anomalies related to reconstruction / restoration activites and geometrical/structural features [14]. As a result, in this work, the material properties analysis has been performed through thermographic surveys gathered by the Camera Avio InfReC R300SR-S Thermal Imager (NEC R300SR). Expected outputs are 2D thermal images of monitored structural elements.

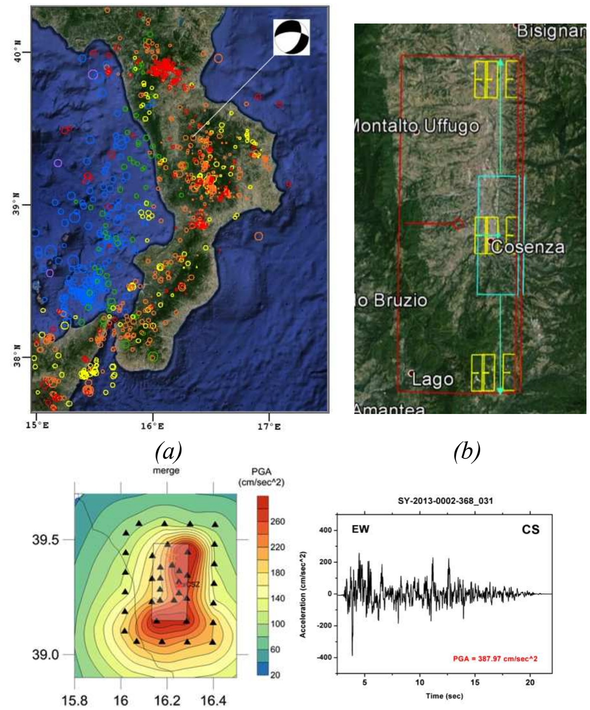
To complement the geometrical/structural and material properties analysis, the survey about building vibration properties has been conceived to evaluate the dynamic properties of buildings, identifying the main resonant frequencies of structural elements with corresponding vibration modes [15]. This information is useful to characterize the response of such elements especially in case of earthquakes, based on their different geometrical, structural and material construction properties. To this purpose, an interferometric RAR campaign has been performed by the IBIS-L© system for vibration monitoring purposes. Expected outputs are line of sight (LoS) displacements (in mm) and PSD (mm^2/Hz) profiles.

3. EXPERIMENTAL RESULTS

In this section, some experimental results are described and discussed to test the effectiveness of the proposed approach.

The test areas adopted for regional-scale & long-term analysis, urban-scale & short-term survey and building-scale & near-real-time analysis are the Calabria region, the town of Cosenza and the Sant'Agostino Historic compound. Calabria region represents an interesting test case since it was struck by many historic destructive earthquakes, which raise its seismic risk at the highest levels in the Mediterranean basin. In this framework, Cosenza town is one of the most important municipalities, characterized by a great variety of valleys, mountains and hills together with a complex and fragile territory. The town suffered several architectural and structural renovations due to earthquake damages, which posed severe consequences for historic heritages, such as the Sant'Agostino Monument compound. Located in the Cosenza old town and strictly closed to the Crati River, the complex was severely damaged by three main hazardous earthquakes (1638, 1870, 1905), which implied deep reconstruction and renovation activities.

Starting from the analysis of the instrumental seismicity, Fig. 2(a) shows the seismicity map of Calabria region for the period January 1st, 2015-February 20th, 2016, where the beach-ball represents the fault plane solution of a small earthquake (mL = 2.5) occurred on February 12th, 2016. This result allows demonstrating the high sensitivity of seismic stations for detecting and characterizing low-magnitude earthquakes in support of seismological studies. To corroborate the analysis of regional instrumental seismicity, some results relevant to the analysis of seismogenic sources are shown in Fig. 2(b) for the town of Cosenza. In detail, red, cyan and yellow boxes highlight seismogenic structures for specific earthquakes of M7, M6 and M5 class magnitudes, respectively. Sample results, obtained by simulating an earthquake of M7 magnitude, are provided in Fig. 2(c). They show the PGA map (left panel) and the synthetic accelerogram along the East-West component (right panel) of the simulated event. Such results can be used to support the analysis of site seismic response and evaluate the dynamic response of structures within Cosenza town.

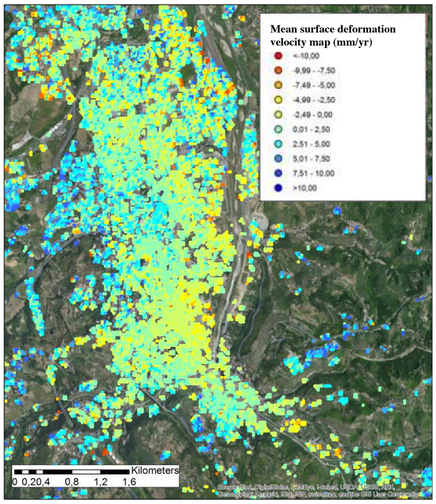


(a) *(b)*

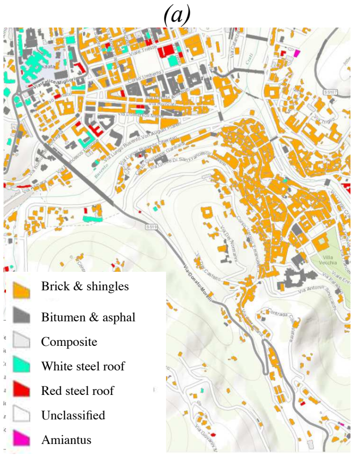
(c)

Fig. 3. Results of seismogenic source analysis in Calabria region. (a) Regional seismicity map. (b) Simulated shaking scenarios for the Cosenza urban area. Red, cyan and yellow boxes correspond to seismogenic structures for M7, M6 and M5 class magnitudes, respectively. (c) Results obtained by simulating an earthquake of M7 magnitude: PGA map (left panel), synthetic accelerograms for the East-West component (right panel).

Zooming at the urban-scale of the Calabria region, some meaningful results relevant to the analysis of surface deformations are shown in Fig. 3(a). The map shows that the Cosenza urban area is characterized by slow surface deformation phenomena with velocity values included in a range of ±2.5 mm/yr for the time period ranging between May 2011 and January 2014. This demonstrates the almost stability of the observed scenario. In detail, negligible subsidence (uplift) phenomena, i.e. deformations away from (towards) the quasi-vertical sensor LOS, can be observed in the whole urban area. To support the analysis of surface deformation processes, the hyperspectral-based land-use classification map of the urban scenario is provided in Fig. 3(b). It allows distinguishing the historic city core from the more recent part of the town, identifying few asbestos roofs of some industrial buildings in the area. Both SAR and hyperspectral analyses provide useful information to map critical areas and buildings exposed to high seismic risks**.**



(a)

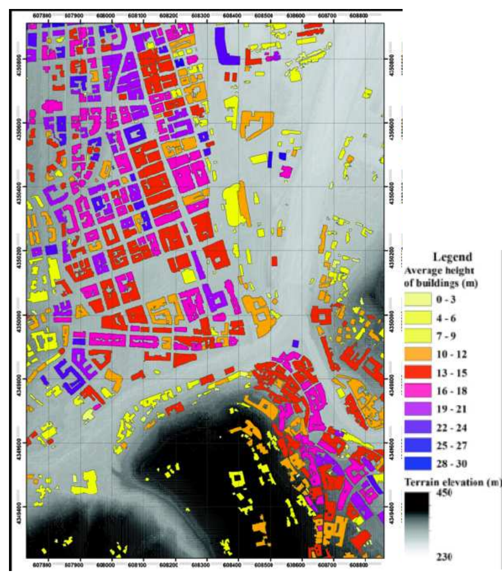


(b)

Fig. 3. Experimental results about the remotely sensed monitoring of Cosenza town. (a) SAR-based Mean surface deformation velocity map (in mm/yr). (b) Hyperspectral-based building roof classification map.

Looking at the same urban-scale, Fig. 4(a) shows the LiDAR-based footprints of the built-up area with average height information (in m), superimposed to the surface elevation (in m) map of Cosenza city core. It can be observed that most of the buildings exhibits average height values lower than about 20 m. The only exception is represented by some critical structures in the recent part of the town (e.g. hospital, schools, etc.) as well as some aggregate buildings and significant heritages within the historic city core (i.e. theatres and religious structures). Most of the buildings within the recent part of the town are located on flat areas with low elevation and slope values. Conversely the old town is located at the top of reliefs with surrounding high-slope areas. As a result, the exposing level of the built-area increases as you move away from the recent part of the town approaching to the historic city core**.**

Following the investigation of local topography and built-up areas, some meaningful results relevant to the analysis of local site seismic response are shown in Fig. 4(b). The HV profiles obtained from the ambient noise measurements at single station in the surroundings of Sant'Agostino Complex show some slight amplification peaks concentrated on a wide band of frequencies (2.8-5.5Hz). This result suggests the presence of a relatively shallow impedance contrast. The variability of the resonant frequency reflects the complex and heterogeneous geology of the area, which is located along an ancient coastline and is characterized by flooding rivers and fluvial deposits of different nature**.**



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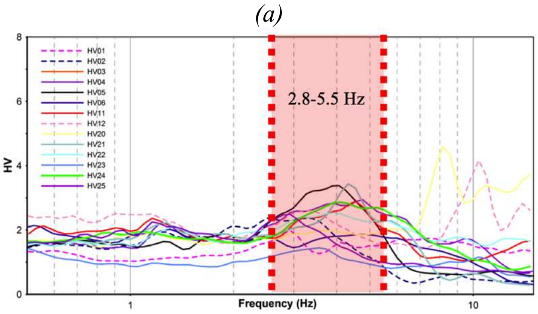
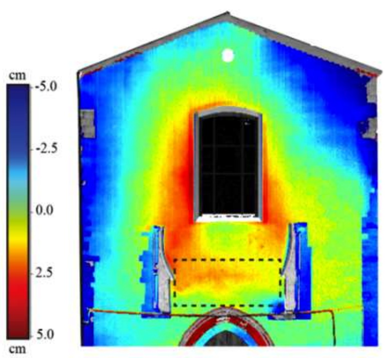


(b)

Fig. 4. Experimental results relevant to the urban-scale & short-term survey of Cosenza town. (a) Building elevation (in m) projected over the DTM. (b) HV profiles of the observed area.

Referring to the building-scale & near-real-time analysis, sample meaningful results relevant to combined use of TLS and infrared thermographic surveys are shown in Figs. 5(a) and 5(b), respectively, for the church façade of the Complex. The TLS-based

2D morphological map (in mm) of the structure, evaluated with respect to a reference fitting vertical plane (see upper panel in Fig. 5a), allows showing some irregularities in central part of the façade (near the window) and immediately above the lancet arch. These results agree with historic surveys of the building: indeed, the first anomaly takes into account the presence of an old rosette window located in place of the current one. Conversely, the second anomaly reveals the presence of a "hidden arch" at the entrance door of the church. Same anomalies are clearly detected by IRT images of the façade, which are properly projected and superimposed to the TLS mesh of the façade.
The analysis about structural and material properties of the church façade are corroborated by InRAR investigations to observe the vibrating properties of the façade during the ringing bells of the tolls at the noon, see Fig. 5(c). Results are provided in terms of PSD profiles evaluated for relevant target points over the façade. They show noisy frequency patterns for the whole structure, which is then poor sensible and stable with respect to bells-induced vibrations (see blue and green curves in Fig. 5c). Conversely, a frequency pattern rich of harmonics is observed for the central window of the façade, which is more sensible to stresses induced by the toll of the bells (see red curve in Fig. 5c). These results allow identifying those elements more sensitive and more exposed to vibrations induced by external stresses.



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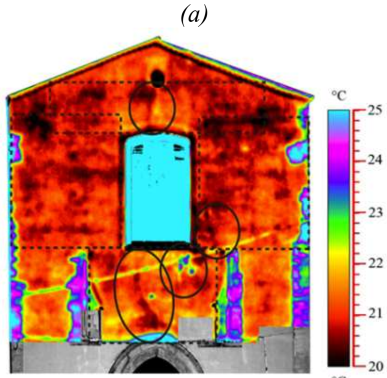

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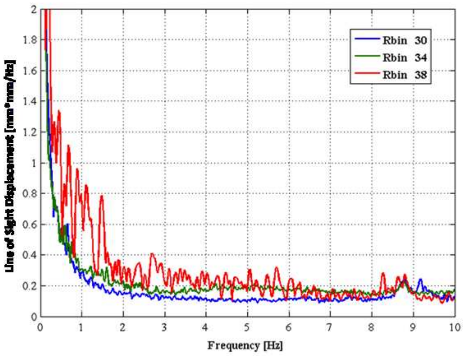


(c)

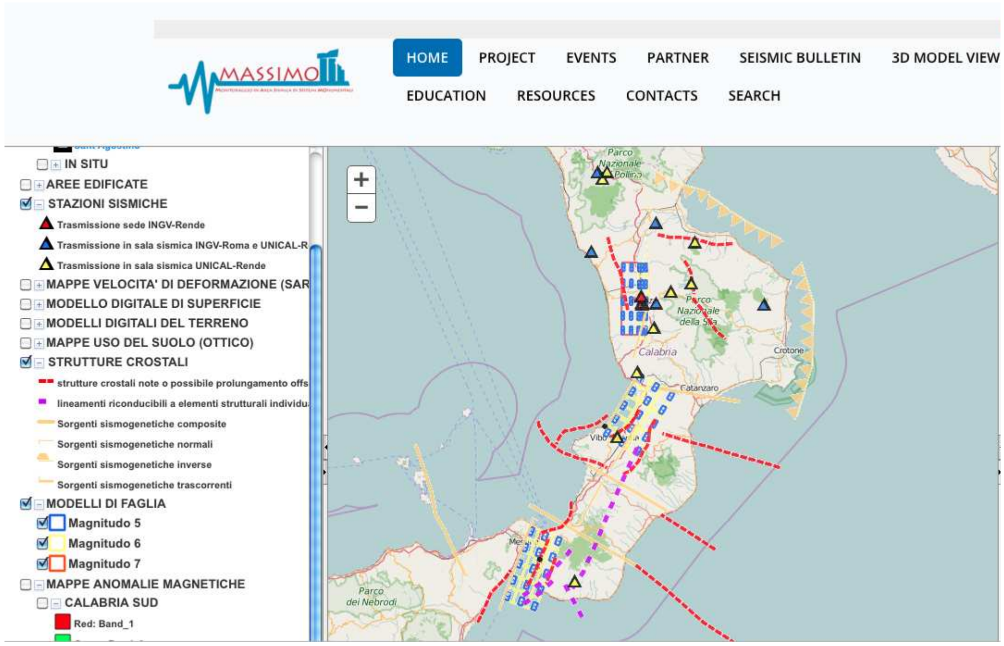
Fig. 5. Experimental results relevant to the monitoring about the church facade of Sant'Agostino Complex. (a) TLS-based 2D morphological map. (b) Infrared thermographic image. (c) InRAR-based PSD measurements.

4. VALUE-ADDED PRODUCTS

All the experimental results, provided by multi-spatial and multi-temporal investigation techniques, have been made available through ad-hoc user-friendly interfaces. The latter allow to access, manage, display, integrate and assimilate multi-disciplinary results. In detail, two different interfaces are provided as value-added products of the whole investigation methodology, namely a web-GIS module and a 3D visual platform. They are connected both between them and to the centralized repository of the MASSIMO system through a dedicated http/https Internet protocol.

The web-based GIS platform (see Fig. 6a) has been developed through an ArcGIS© infrastructure to provide a complete and exhaustive interface for the web-based visualization, management and post-processing of geospatial data. The latter refer to the results of investigation gathered at regional and local scales for long and short-term surveys, respectively. The platform consists of three different interfaces: (a) a desktop environment, to manage, display and post-process data stored in the MASSIMO storage; (b) a server interface, to manage and organize the geospatial database; (c) a web-service interface, to provide interactive maps and results to final end-users.

The 3D / 4D visual platform (see Fig. 6b) has been developed through a dedicated 3D Manager software for the visualization and the use of data coming from the building-scale & near-real-time surveys of monitored historic buildings. The platform allows the interactive navigation of the structure within a 3D spatial domain. Each geometrical element can be modified dynamically and contain information about attributes coming from multi-disciplinary investigations. This aspect justifies the 4D nature of the platform. All the data can be provided with stereoscopic functionalities. Moreover, they can be accessible to different end-users based on requested information and professional skills.



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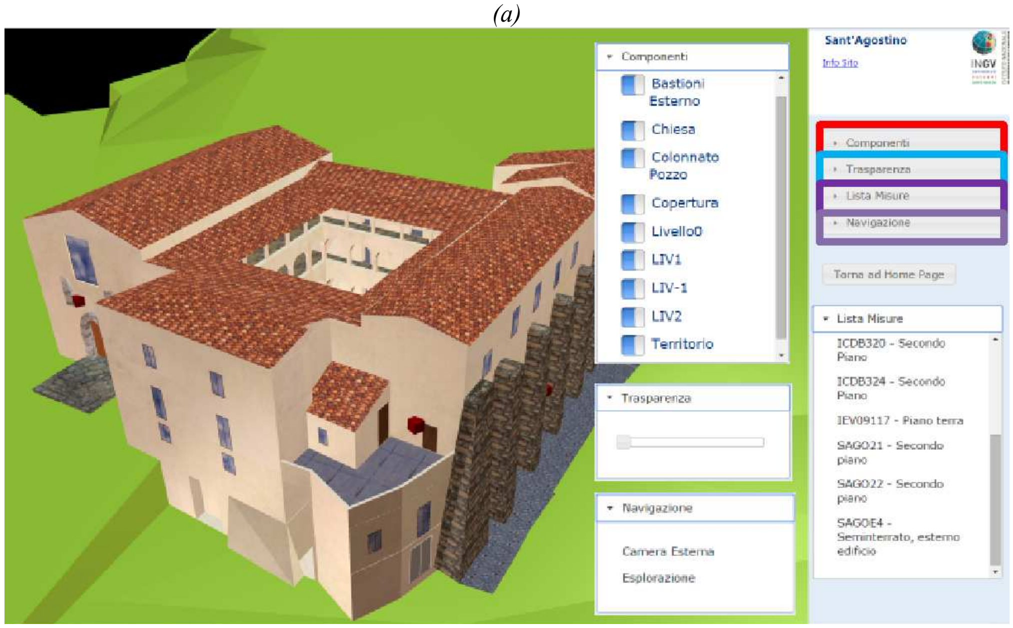

(b)

Fig. 6. Value-added products of the proposed methodology. (a) The web-based GIS platform. (b) The 3D/4D visual platform

5. CONCLUSIONS

In this paper, an innovative monitoring system called MASSIMO is presented for the seismic risk monitoring of cultural heritage. Based on a multi-sensors infrastructure, a modular, scalable and portable methodology is implemented and tested for monitoring historic buildings at different spatial (regional, urban, building) and temporal (annual, monthly, daily, hourly) scales. It combines classical techniques, proximal, airborne and space-borne remote sensing tools, geophysical surveys and seismogenic analysis of the territory, for seismic risk monitoring purposes. The proposed approach allows to access, manage, display, integrate and assimilate results coming from multi-spatial and multi-temporal investigations by means of user-friendly interfaces, namely a web-GIS module and a 3D visual platform. The latter represent the value-added products of the whole investigation methodology. Experimental results, obtained for the Calabria region, the town of Cosenza and the Sant'Agostino Complex, show the effectiveness of the proposed approach. The latter can be used to provide guidelines to local and national Institutions about possible consolidation / restoration / prevention planning for the safeguarding of historical buildings.

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