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Integrated GPR surveys and 3D modelling of the Sforza Castle's underground network

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ABSTRACT

The research on Castello Sforzesco in Milan developed an integrated 3D information model combining historical sources and contemporary survey technologies. A digital twin was structured through multiple Levels of Geometric Information (LOGI), organized by attributes and accuracy of the original information. The system was conceived not only as a repository of knowledge, but also as a dynamic analytical environment capable of stimulating new research questions and supporting further investigations. This potential led to collaboration between the Politecnico and Codevintec Italiana s.r.l., resulting in a wide survey with ground-penetrating radar. The Ground Penetrating Radar (GPR) investigations conducted within the Milanese fortress area, which ultimately led to significant discoveries, were themselves the result of studying this model. Extensive investigations were carried out using stepped-frequency array and single-channel impulse GPR systems, enabling high-resolution mapping of the castle's underground infrastructure and surrounding defensive structures. The results revealed an unexpectedly complex subterranean network, including buried corridors, connecting tunnels, and a "twin" counterscarp gallery, drawn by Leonardo da Vinci and now located a few centimeters from the currently accessible one. The surveys also provided significant physical evidence supporting the existence of the legendary underground passage between the castle and Santa Maria delle Grazie. The results obtained have demonstrated the effectiveness of the multidisciplinary approach for the exploration of complex heritage sites. The research highlights how digital twins enriched with non-invasive diagnostic data can evolve from simple static representations into powerful interpretative and decision-support tools for the conservation, analysis, and enhancement of cultural heritage.

1. Introduction

Nowadays, building management relies on technologies and solutions that make it possible to establish a relationship between geometric representation (often in three-dimensional form) and informational datasets. However, this approach is no longer limited to new constructions and BIM (Building Information Modeling) systems, but now concerns the entire built environment, particularly architectural cultural heritage. In a broader sense, this concept is referred to as the digital twin. In recent years, experimentation in this field has been extensive and continues to grow, testing a wide range of approaches and tools. These include Scan-to-BIM (or HBIM) processes, as well as integration with ICT (Information and Communication Technology) solutions such as VR (Virtual Reality), AR (Augmented Reality), and MR (Mixed Reality) [1]. Additional developments include online platform-based solutions [2], as well as ad hoc systems specifically designed to address the particular requirements of individual case studies. In the context of architectural heritage, the challenge lies in identifying and proposing solutions capable of managing both the irregularities of historic structures and the heterogeneity of the collected data, including metric information as well as informational datasets.

The current landscape remains highly fragmented across a wide array of sub-themes, resulting in multiple research directions. Consequently, there exists a broad variety of digital twins that, each in its own way, interprets reality by generating a tailored replica of a building based on the information available and processed. These digital twins address different requirements and serve diverse functional objectives, such as accessibility, knowledge, management, and conservation. This plurality of purposes inevitably influences the internal structure and development process of each model, which can vary considerably

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depending on the intended final use, even though they often originate from the same data source, namely a point cloud acquired via laser scanning or photogrammetry [3]. This remains particularly true when the digital twin is used to represent an existing physical object. However, these tools are also frequently employed for reconstructing the historical layers of a building, serving as the platform where lost geometries can be digitally brought back to life [4,5]. A digital twin may also be defined as a digital counterpart of an object or system that simulates its processes and dynamics. It should therefore provide the necessary information aligned with the specific function for which it was conceived and developed. While this concept is already well established within the BIM domain and new building models, it still represents an open field of investigation when applied to the existing built heritage. This has led to a growing body of experimentation and research [6–8] aimed at exploring how to best exploit such datasets and examine their integration with the components of the digital building.

From the current scenario, what increasingly emerges is the great potential offered by approaches capable of managing different levels and types of information through highly heterogeneous datasets. When dealing with architectural heritage, it is essential to bear in mind that achieving an adequate and in-depth understanding of a complex and stratified building, both from a material and historical perspective, often requires working on multiple fronts. Integrated approaches [9,10] adopted during the knowledge phase, combining surveys and investigations of various kinds, make it possible to reveal the multiple aspects of buildings. Precisely because of the non-homogeneous nature of the source data, it is becoming increasingly crucial to address the theme of the digital twin from the perspective of developing management tools capable of collecting and handling such diverse datasets and metric information, all of which are equally important for understanding the built heritage.

In this framework, non-invasive diagnostic tools such as Ground Penetrating Radar (GPR) based on stepped frequency techniques can play a fundamental role. GPR enables the investigation of subsurface and inner structural features of buildings, providing crucial geometric and material data that are often inaccessible through traditional survey methods. When integrated into a digital twin, these high-resolution datasets enrich the model with detailed information about the hidden or embedded components of the built environment, such as voids, reinforcements, or degradation patterns, thus enhancing its accuracy, reliability, and predictive capabilities. The ability to perform repeated surveys also supports the temporal dimension of digital twins, allowing for condition monitoring and lifecycle management of structures over time [11].

The present study positions itself within this context, developing a novel approach to the knowledge and management of architectural heritage, supported by contemporary surveying techniques and technologies for the study and digital transposition of information. The proposed framework is capable of representing existing structures, lost elements, and hypothetical reconstructions within a unified model, combining information from diverse sources that vary in both nature and accuracy. The goal has consistently been to produce a working model able not only to organize the knowledge related to a heritage asset and facilitate its interpretation, but also to serve as a dynamic tool, capable of evolving over time and fostering new investigations and research insights, such as the one that will be described. This latter aspect, namely the ability to stimulate the advancement of studies and the deepening of knowledge of the built heritage, constitutes the core of the present contribution, which shows how the study of the 3D model has led to new and valuable analyses and discoveries concerning the heritage asset. The fundamental novelty of this work lies in reversing the traditional digital twin workflow: instead of utilizing geophysics merely as an initial data-gathering phase to construct a static model, the pre-existing 3D structured informational model (LOGI) was actively employed as a predictive analytical framework. By identifying spatial contradictions and missing layers within the digital twin, we formulated targeted archaeological and structural questions that directly guided subsequent multi-channel array and impulse GPR surveys in an extremely complex and saturated urban environment. This bidirectional integration marks a significant advance in the state of the art for cultural heritage management, transforming the digital twin from a repository into a proactive research catalyst.

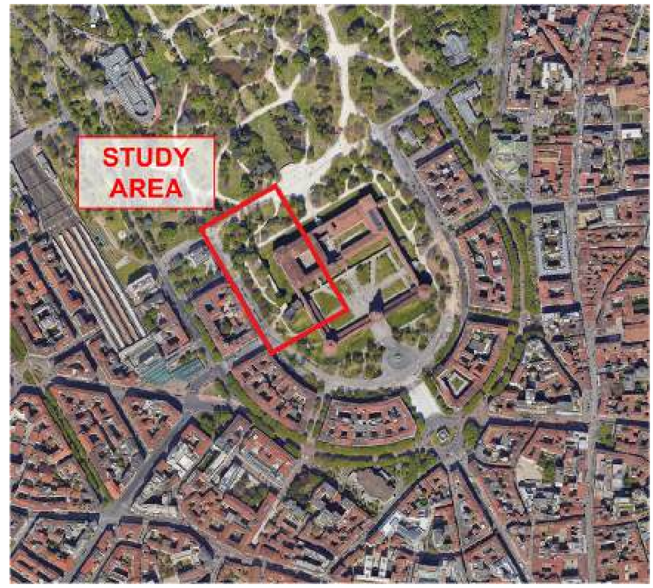

Fig. 1. Zenithal view of the Castello Sforzesco (Google Earth) with the study area highlighted.

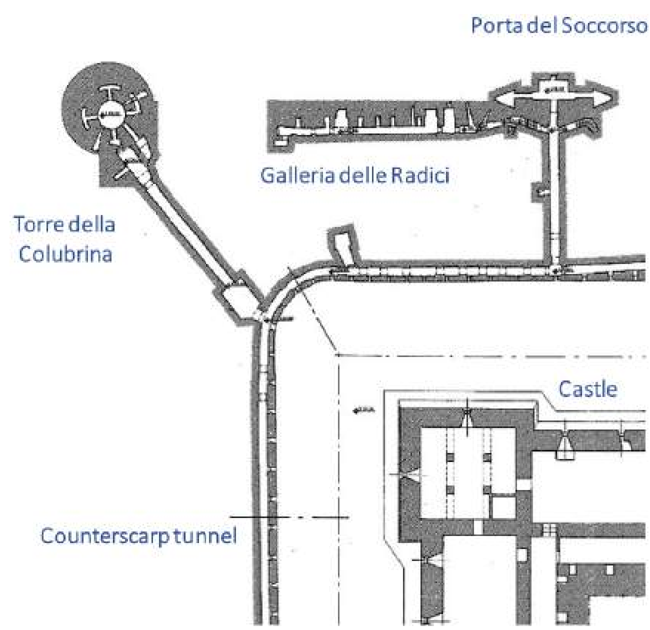

Fig. 2. Underground infrastructure of the Ghirlanda (well-known and accessible spaces).

2. The case study

The activities were carried out at the Castello Sforzesco in Milan (Fig. 1) [12,13], a highly stratified architectural and archaeological context, shaped by successive historical phases that deeply transformed its structure and function over the centuries. Originally founded by the Visconti family in the 14th century, the fortress was extensively

Fig. 3. Views of part of the point cloud implemented for the development of the 3D model.

reworked during the Sforza domination, when it was converted into a ducal residence enriched by contributions from artists and architects such as Bramante and Leonardo da Vinci. Later Spanish domination in the 16th century radically redefined the complex as a military citadel, leading to major defensive expansions, including the construction of the Ghirlanda system. Further modifications occurred during the Austrian and Napoleonic periods, while the restoration campaign led by Luca Beltrami at the end of the 19th century aimed to recover the original appearance of the castle. In pursuing this objective, Beltrami removed several elements belonging to the later historical stratifications, including parts of the Ghirlanda defensive system, which he considered a subsequent [14]. Today, only limited above-ground remains and underground structures of the Ghirlanda survive. The activities carried out focused on the underground and above-ground spaces of the north-eastern sector of the fortress complex (Fig. 2), as well as on the surviving portions of the Ghirlanda system, the outer defensive infrastructure surrounding the main castle core and partially demolished at the end of the 19th century.

The Milanese stronghold immediately proved to be an ideal case study for these tests, due to its complexity and stratification, as well as being a strong catalyst for the subsequent geophysical investigations and GPR surveys, considered necessary following the study of the model. Indeed, Ground Penetrating Radar (GPR) immediately played a key role in investigating hidden structures [15] and potential underground passages within the castle complex. The use of a 3D step-frequency GPR system enabled extended-area mapping with high resolution and improved depth penetration, making it possible to identify inaccessible or lost elements with greater accuracy. These data were integrated into the digital twin, supporting archaeological interpretation and enriching the model beyond the visible layers.

3. 3D information model structure and development

The work carried out on the Castello Sforzesco enabled the development and testing of a new approach to the digitisation of architectural heritage. The fundamental idea is that the digital twin should be capable of collecting data from a variety of sources and representing both existing structures and those that have been lost. This stems from the belief that only such a tool can provide a comprehensive description of a historic building and the processes that have shaped it and are still ongoing [16]. Typically, this type of architecture is associated with a vast body of documents, written works and information accumulated throughout its existence. These are supplemented by more recent sources, such as photographic material, both traditional and modern surveys, etc. All these sources yield geometric information with varying levels of accuracy. The system devised aims to arrange together all geometric data available on an architectural asset, including that which will be produced or updated in subsequent phases. The goal is to provide a tool that supports and facilitates the understanding of complex structures and is capable of both incorporating future data and, above all, stimulating new studies and questions about the architectural heritage.

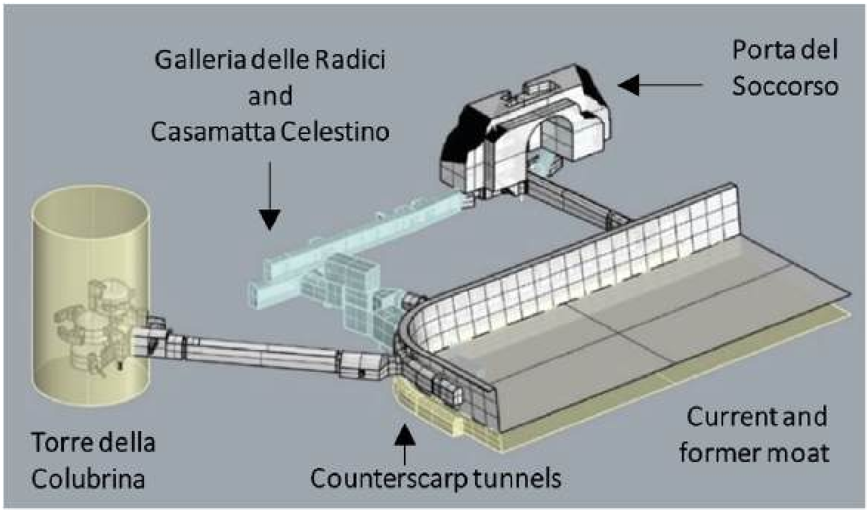

Fig. 4. Portion of the 3D information model of the Castello Sforzesco showing elements pertaining to all three LOGI.

The proposed structure is based on the notion of LOGI [17]: Level of Geometric Information. The digitisation method is structured around a three-tier classification of data, into which the different elements of the building are then catalogued and modelled. The definition of these modelling levels draws inspiration from the LODs (Levels of Development) associated with BIM processes, as well as from other research initiatives that have developed classification systems for levels of detail in modelling [18].

The classification system of sources, and of the resulting 3D elements derived from the information they contain, is currently composed of the following three levels. Within each of these levels, the modelled volumes display a consistent degree of accuracy, determined by the nature of the information and the sources considered.

LOGI 1. This first level concerns the 3D modelling of hypotheses derived from historical documentation (iconographic material, ancient texts, historical cartography, etc.…) and thus produces simple three-dimensional elements representing structures that are no longer visible but were likely once present.

LOGI 2. This level includes documents produced using traditional surveying methods, such as classical geometric surveys and trilateration.

LOGI 3. This represents the highest level in terms of detail and precision; information and materials from modern geomatic surveys fall within this category. Examples include point clouds and surveys with a precision of a few millimetres (Fig. 3). In LOGI 3 the 3D modelling of architectural elements involves a simplification factor with respect to the accuracy of the survey. Since the objective is to develop a tool to support the understanding and management of assets, this approach was deemed acceptable, even though the outcome still provides a reliable and accurate model capable of conveying the necessary information.

It is important to highlight that, despite the manipulation of information and its potential simplification, during the exploration of the model, it is always possible to access the original reference information, allowing consultation of the original data and sources. The 3D model is in fact paired with an information management system [19]. The system requires that all modelled elements within the 3D environment be linked to attribute tables (likewise the structure of the national Topographic Database) that describe them and contain the essential data for identifying each object and its connections to the source documents. Indeed, each attribute table always contains a link to the original resource used, whether it is a document or the survey output, located in a specially created online repository.

The result is an organic yet heterogeneous collection encompassing all elements of the building, from those still accessible to those hypothesised, no longer visible or no longer extant. Moreover, by developing the digital twin in multiple blocks and employing a rigorous georeferencing strategy, each element of the 3D model can be continually updated with new data.

Fig. 5. Comparison between the 3D model of the Bastions, the Theresian Cadastre and today's DTB.

Based on this structure, the 3D information model of the studied section of the Castello Sforzesco, the north-eastern corner of the Ghirlanda complex, was developed. This area includes above-ground elements as well as a considerable underground infrastructure composed of tunnels and small- to medium-sized rooms, the result of the modelling phase is shown in Fig. 4. The elements of LOGI 1, based on historical documents, are shown in yellow. These are the Torre della Colubrina, the original plan of the moat and the second counterscarp tunnel. The Casamatta Celestino and the Galleria delle Radici are shown in blue, obtained from the drawings of a previous traditional survey and pertaining to LOGI 2. Finally, in grey, the elements of LOGI 3, surveyed using photogrammetric and laser scanning methods; these are the current moat, the casemates of the Colubrina Tower (underground), the Porta del Soccorso and the accessible infrastructure of the counterscarp

Fig. 6. GPR systems employed during the survey at Castello Sforzesco. From left to right: the Kontur array; the GSSI UtilityScan and the GSSI Flex NX.

tunnel.

From the outset, the developed tool proved highly valuable not only for understanding the architecture, but also, perhaps more importantly, for raising thought-provoking issues and providing avenues for further study and research. This highlights the intrinsic potential of such a digital object to enable continuous improvement and enrichment, as exemplified by the GPR survey carried out.

Numerous questions emerged from the study of the model and its data, but two directed and paved the way for the subsequent extensive ground-penetrating radar (GPR) survey, which led to the major discoveries presented in the following chapter. The first concerned the Spanish Bastions (Fig. 5), which no longer exist, or perhaps are simply no longer visible. By examining the model and comparing that area with the Topographic Database (DBT), the question arose as to how much of these structures might still be present beneath the ground level of Parco Sempione or the adjacent streets, an issue that could be addressed through non-invasive geophysical investigation. The second issue relates to theories concerning a second counterscarp gallery, which some have posited lies just below the floor level of the currently accessible gallery. However, this hypothesis appears to conflict with what can be visualised in the model.

These and other questions formed the foundation for the continuation of research at the Milanese fortress, which led to unexpected discoveries and new data with which to test the model and its structure.

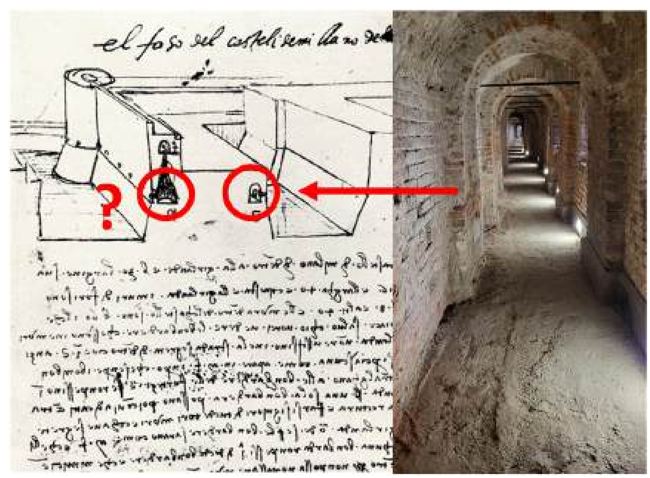

Fig. 7. The red circles highlight the two galleries: the one on the right corresponds to the accessible counterscarp gallery (red arrow and photo), while the one on the left (question mark) represents one of the "twin" galleries discovered during the GPR campaign. On the left, a drawing by Leonardo da Vinci (Codice B, f. 36 v.).

4. GPR-based investigations at the Castello Sforzesco

The primary geophysical investigation was conducted using different GPR systems in relation to the site's complex logistics. To provide a comprehensive operational view of the non-invasive diagnostics, the survey strategy, acquisition parameters, and processing pipelines are detailed below:

a) Raw Data Initial Interpretation & Gaps Identification

The preliminary diagnostic phase was directly stimulated by structural and geometric ambiguities identified during the exploration of the unified 3D LOGI model. As already mentioned two major architectural missing links emerged: the demolished 16th-century Spanish Bastions and, the parallel underground defensive circuit. Initial evaluation of GPR data profiles revealed highly cluttered, hyperbola-dense signal domains beneath the ground surface of Parco Sempione and inside the accessible counterscarp masonry gallery. These subsurface reflections required systematic interpretation to identify target structures, historical debris and urban background layers.

b) Modelling Description and Survey Strategy

The acquisition strategy was custom-tailored to handle the complex logistical constraints of the fortress using three distinct systems. (Fig. 6). To ensure precise multi-source data fusion, the data acquired across the external large-scale areas were strictly georeferenced using an RTK GNSS receiver. Conversely, inside the underground counterscarp galleries where satellite signals are entirely absent, the spatial reference was locked using local benchmarks and physical control points meticulously measured to ensure accurate structural alignment and positioning within the global coordinate environment.

The different systems are:

- The Kontur Stepped-Frequency Continuous-Wave (SFCW) Array system, featuring a 1.80-meter-wide antenna structure with 20 parallel channels operating across a broad 200–3000 MHz frequency spectrum, was deployed across the expansive external fields of Parco

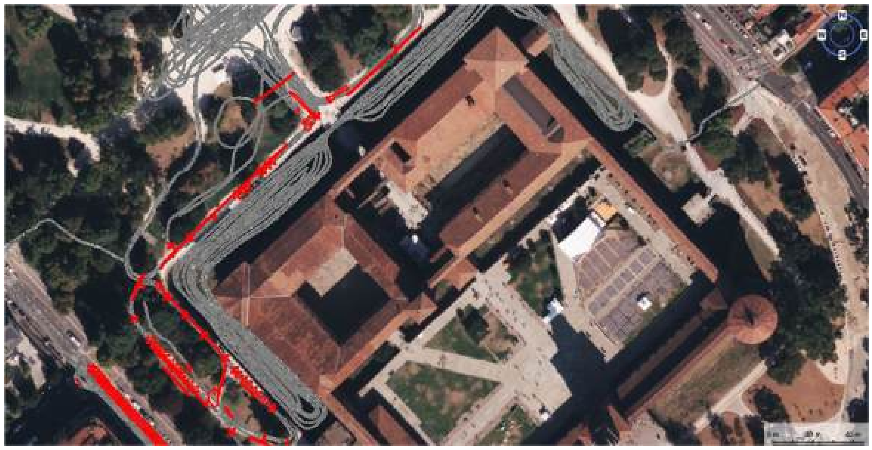

Fig. 8. The red lines indicate all underground structures identified through GPR surveys. The grey traces represent the areas covered by the GPR survey.

Sempione. This setup aimed to perform full 3D subsurface mapping of deep foundations while overcoming single-channel sampling gaps.
- The single-channel GSSI UtilityScan (equipped with 200 MHz and 350 MHz central frequency impulse antennas) was utilized inside narrower trenches, smaller external rooms, and the internal pathways of the counterscarp gallery to balance depth penetration and resolution.
- The high-frequency GSSI FlexNX system was selectively operated inside the gallery to map localized, high-resolution masonry layers, wall composition thicknesses, and structural vaults.

The spatial survey design directly integrated the historical layouts digitized in LOGI 1. Specifically, Leonardo da Vinci's sketches in Codex B (Bibliothèque de l'Institut de France), which explicitly outline a "strada segreta di dentro" (inner secret road) within parallel defensive galleries, served as the physical positioning matrix for the high-density grid tracks (Fig. 7, Fig. 8).

c) Processing Steps and Technical Rationale

Advanced data processing was carried out using Examiner (for SFCW array data) and RADAN software (for impulse single-channel data) to isolate meaningful targets from the dense urban electromagnetic noise characterizing the site. The processing sequence prioritized time-zero correction and band-pass filtering to clean the raw signal, followed by background removal algorithms applied specifically to clear flat horizontal noise bands and suppress continuous ringing reflections between the antenna and the ground. This subtraction was essential to uncover hidden vertical hyperbola apexes. Regarding the Kontur stepped-frequency array data, a specific Inverse Fast Fourier Transform (IFFT) was performed, incorporating a frequency cutoff that eliminated high frequencies above 1500 MHz; this specific step aimed to evaluate whether preserving only the lower frequency spectrum could effectively enhance signal penetration and maximize depth visualization. Furthermore, a rigorous velocity analysis was performed across the datasets to calculate the true electromagnetic propagation speed within the local medium, providing a reliable calibration for accurate depth estimations of the anomalies. Finally, manual gain corrections countered signal attenuation, and radar migration collapsed the remaining diffractions, transforming the cleaned reflections into sharp, geometrically accurate boundaries representing the structural realities of the subsurface.

The GPR survey conducted at Castello Sforzesco has unveiled a more extensive and intricate underground network than previously documented (Fig. 8), bringing to light numerous anomalies suggestive of buried structures and unrecorded tunnels. Preliminary evidence of corridors and chambers adjacent to the counterscarp gallery emerged from the analysis of GPR depth slices. This is a series of interconnected tunnels branching off near the current moat, forming part of the intricate internal infrastructure of the Ghirlanda of the Castello Sforzesco. Among these passages, however, one stands out in terms of importance, as its existence and position have long been the subject of debate. The results clearly illustrate both the known counterscarp gallery and a parallel structure, hereafter referred to as the 'twin gallery' (Fig. 9).

Beyond the primary castle core, the wide-area 3D mapping with the Kontur system enabled a "digital excavation" of the castle bastions area, revealing repetitive geometric targets measuring approximately 0.60 m

Fig. 9. The depth slice image shows the parallelism between the known counterscarp gallery and the unknown "twin" gallery.

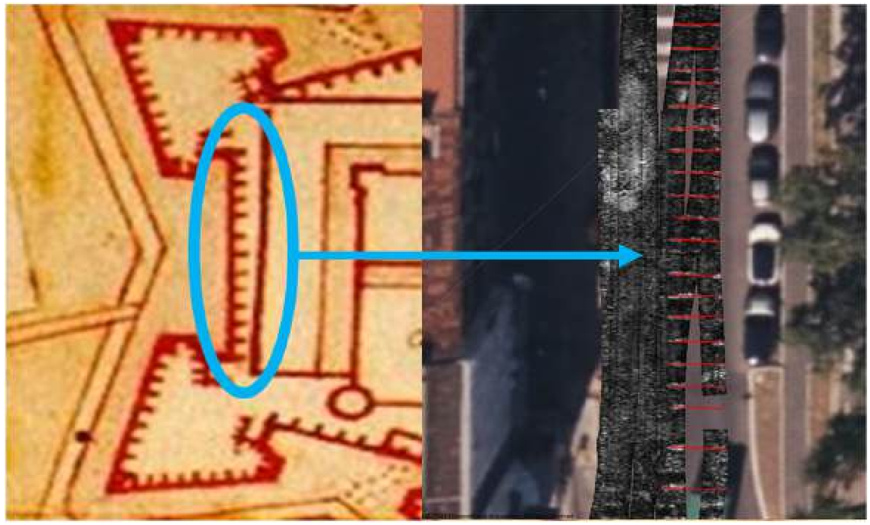

Fig. 10. Comparison between historical cartography and 3D GPR mapping of the castle bastions. The ripetitive targets align perfectly with the historical record, providing scientific evidence of the buried foundations of the bastions beneath the current street level.

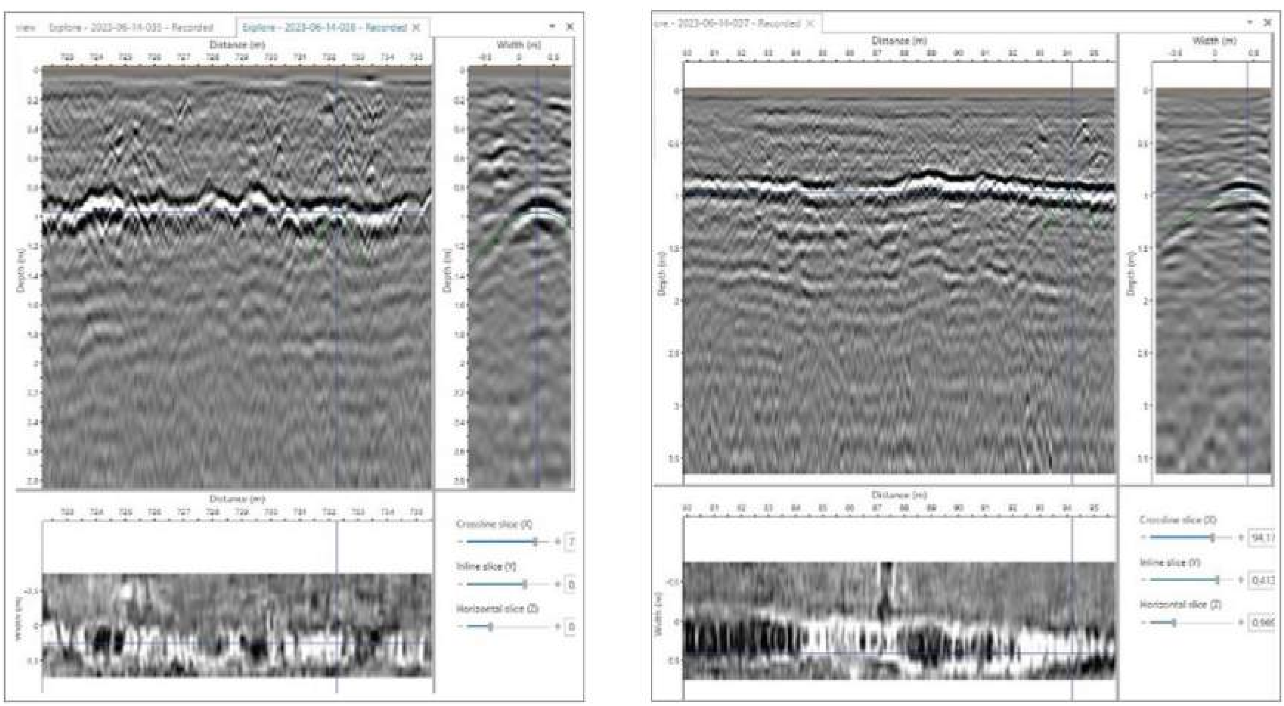

Fig. 11. The GPR profile of the newly discovered anomaly (left) presents a hyperbolic signature nearly identical to that of the known counterscarp gallery (right), confirming its nature as a parallel, man-made structure.

by 3 m each, aligned and arranged at regular intervals, approximately 0.90 m apart (Fig. 10). While these could initially be mistaken for modern debris, the particular 3D visualization of the buried foundations aligns perfectly with the 16th-century Spanish defensive perimeter demolished in the late 1800s. This assumption is supported by the coeval of other contemporary defensive structures located within the innermost ring of the city of Milan. The uncovered layout, in fact, shows strong parallels with the bastions found in the Porta Romana area and its structures. The survey revealed several anomalies characterized by regular geometries and alignments that closely correlate with the site's documented features, specifically the counterscarp gallery. This suggested the presence of parallel or interconnected subterranean routes. To substantiate this hypothesis, a detailed comparative analysis was conducted between the GPR data from the established gallery and the newly identified features. As illustrated in Fig. 11, the two datasets exhibit a striking correspondence: the geometric configuration, depth, and cross-sectional dimensions of the targets are identical in both cases. Specifically, this second gallery is also approximately 1.60 m wide, like the one currently accessible; it is likewise vaulted, with the keystone located about 1 m below the ground level of Parco Sempione. Furthermore, the depth slice of the known gallery clearly displays a perpendicular tunnel section branching toward the unknown one, providing physical evidence of a connecting corridor between the two environments. This remarkable similarity in geophysical signatures, combined with the identification of structural links, provides conclusive evidence that the anomaly represents a second, previously undocumented gallery,

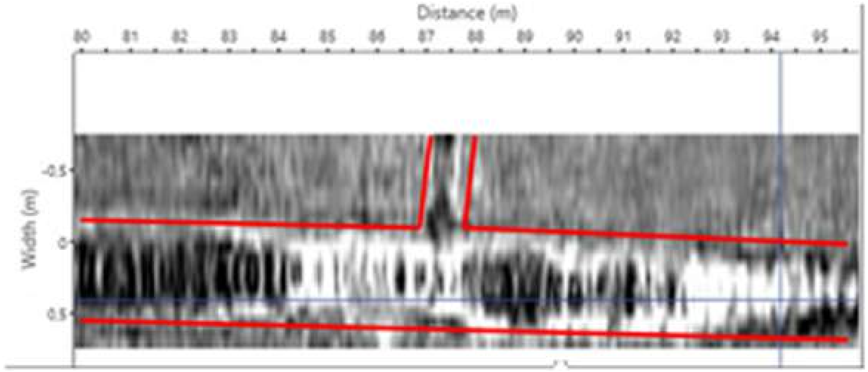

Fig. 12. The perpendicular tunnel provides physical evidence of an interconnected subterranean passage network leading toward the newly discovered "twin" gallery.

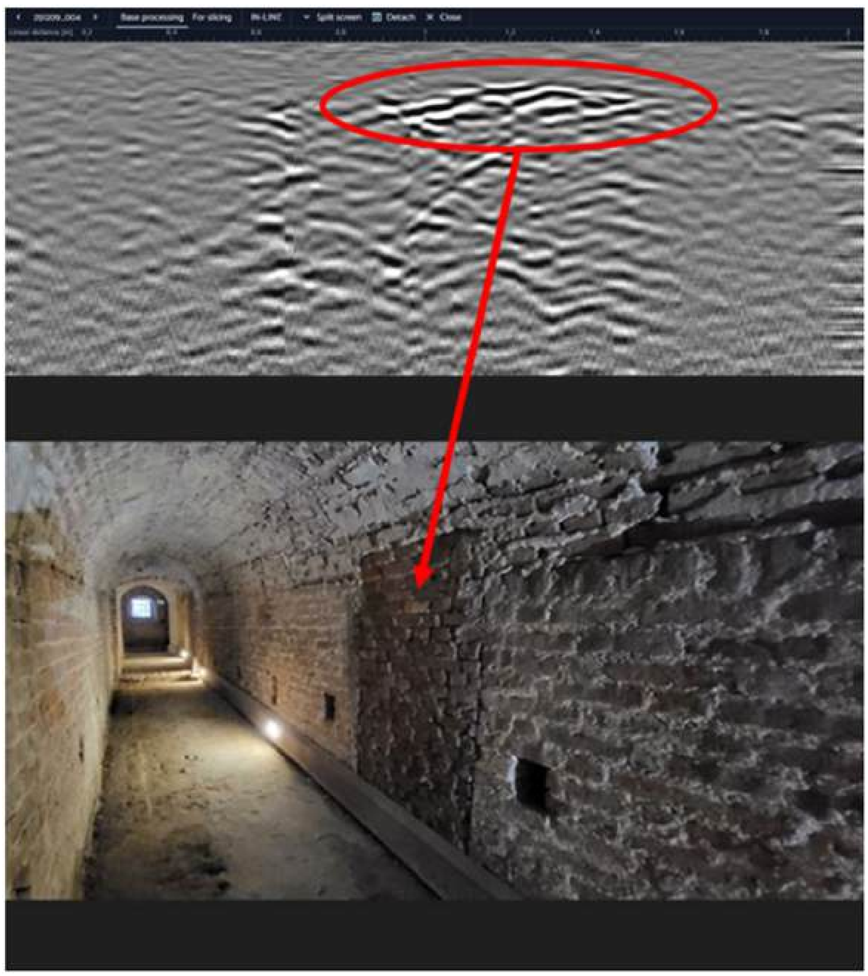

Fig. 13. The perpendicular tunnel provides physical evidence of an interconnected subterranean passage network leading toward the newly discovered "twin" gallery.

running parallel to the known accessible structure. The planimetric view (depth-slice) (Fig. 12) further confirmed this layout, showing not only the parallel galleries but also evidence of interconnecting passages between the two environments, precisely as hypothesized in Leonardo's defensive designs.

In specific areas, visual inspections of sealed or partially obstructed corridors directly corresponded with GPR signals that showed clear continuations of these passages beyond the visible blockages. In particular, evidence of masonry infills was visually identified at the exact coordinates where the 3D planimetric data indicates the junction points with the interconnecting tunnels. The interpretation of these results was greatly enhanced by using Flex NX for a detailed characterization of the structural layers. Specifically, the Flex NX allowed for the scientific detection of the "voids" hidden directly behind these infills (Fig. 13).

Among the most significant findings, the survey identified a clear, continuous anomaly consistent with the passage frequently mentioned in historical records and local legends-most notably, the hypothesized

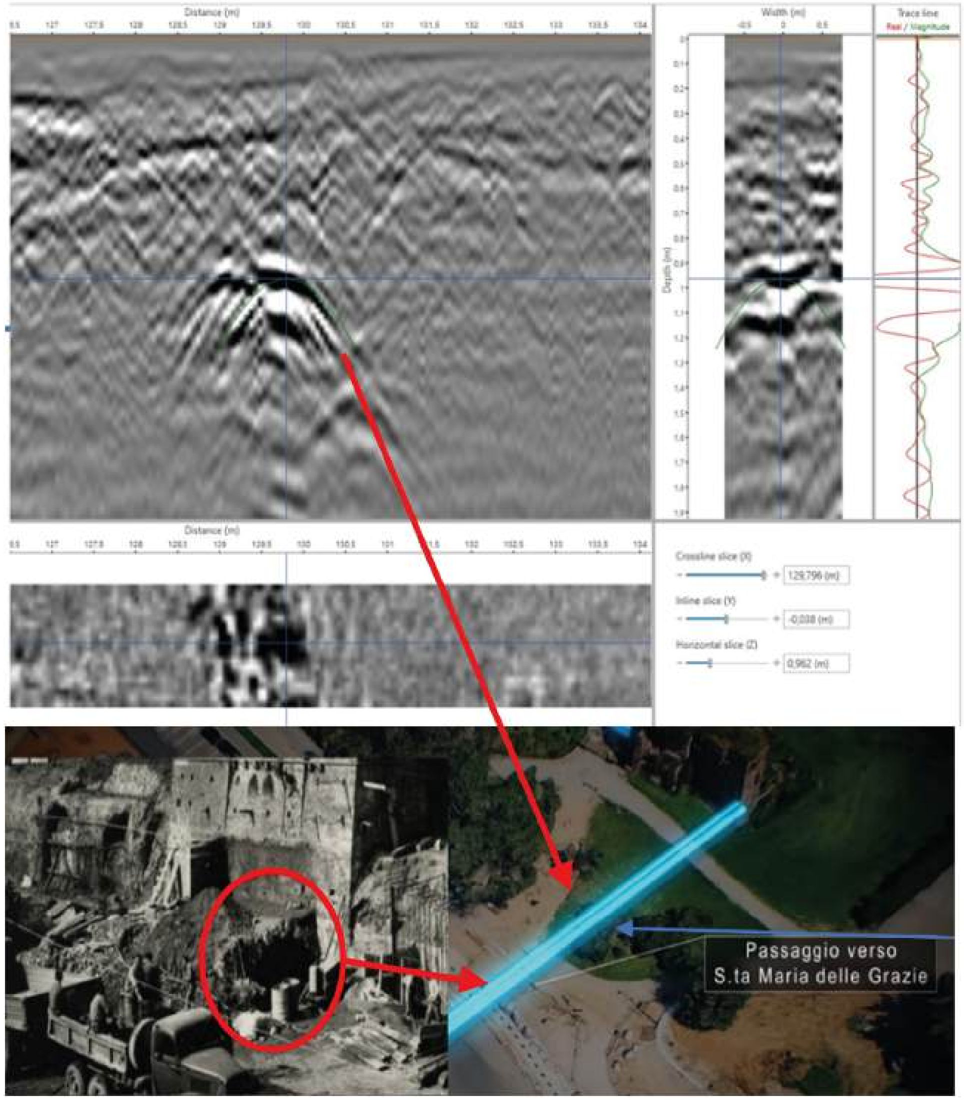

Fig. 14. The GPR data (above) provides scientific validation for the historical evidence (below). The GPR profile reveals a clear hyperbola confirming a structure. The historical photo shows the tunnel entrance during past excavations.

underground connection between the castle and the church of Santa Maria delle Grazie. This provides the first substantial physical evidence supporting the existence of the tunnel said to have been used by Ludovico Sforza to secretly visit the tomb of his wife, Beatrice d'Este. The compelling evidence for this discovery is presented in Fig. 14, which integrates the historical photograph of the tunnel with the corresponding GPR data that scientifically validates its presence. This information does not resolve the wide range of issues related to the legendary passage; however, it certainly represents an important contribution to the reconstruction of the structure and a catalyst for further considerations and investigations.

This information does not resolve the wide range of issues related to the legendary passage; however, it certainly represents an important contribution to the reconstruction of the structure and a catalyst for further considerations and investigations. Finally, the interpretation phase fully cross-referenced 2D cross-sectional slices with full 3D spatial visualization blocks. As showcased directly in Fig. 15 and Fig. 16, the volumetric data blocks are seamlessly integrated into the georeferenced architectural point cloud environment, confirming structural continuities across all dimensions.

5. Conclusions

The work carried out has clearly reaffirmed the usefulness of geophysical investigations, specifically GPR (Ground Penetrating Radar) surveys, for the non-invasive exploration of the subsurface. Moreover, the activities conducted on the Milanese case study enabled the validation of the effectiveness of the proposed and tested framework for the development of the 3D information model. The survey successfully identified various defensive tunnels, many of which show clear geometric and spatial connections to structures already known within the castle complex. These include multiple parallel galleries and interconnecting corridors, which suggest a highly organized and extensive underground defense system (Fig. 15). This is exemplified by the discovery of the "twin" counterscarp gallery, which perfectly matches the defensive engineering principles described in Leonardo da Vinci's historical sketches. Notably, the investigations also brought to light strong evidence of the tunnel connecting the Castello Sforzesco to Santa Maria delle Grazie. Although further confirmation of the tunnel's layout will require additional studies and surveys, the extensive investigation using the Kontur and GSSI GPR has enabled a broad and high-resolution mapping with improved signal penetration.

The integration of 3D GPR data with the 3D model and its

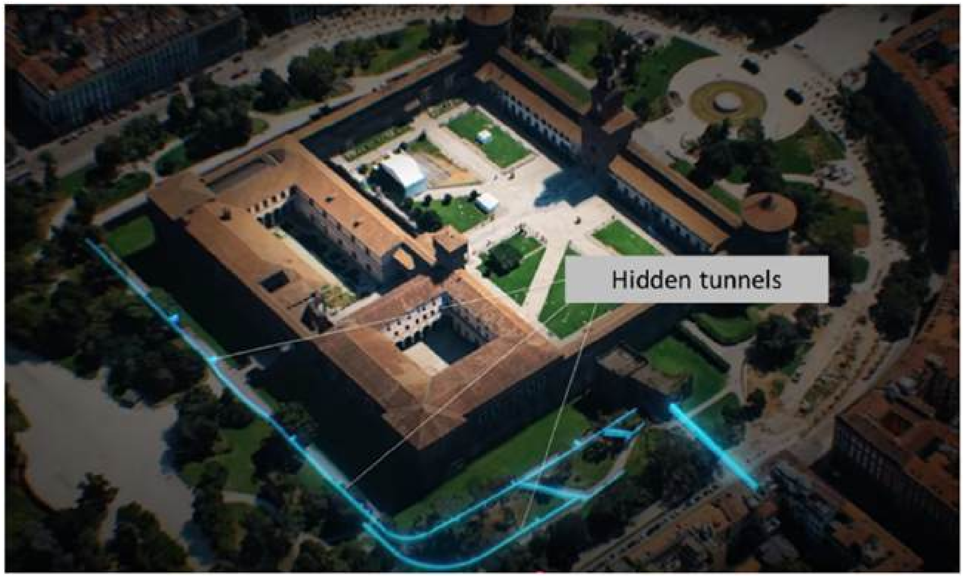

Fig. 15. Visualization of the intricate network of undiscovered tunnels and underground passages identified during the GPR campaign at Castello Sforzesco. The blue light overlays emphasize the extent of the hidden infrastructures within the castle's perimeter.

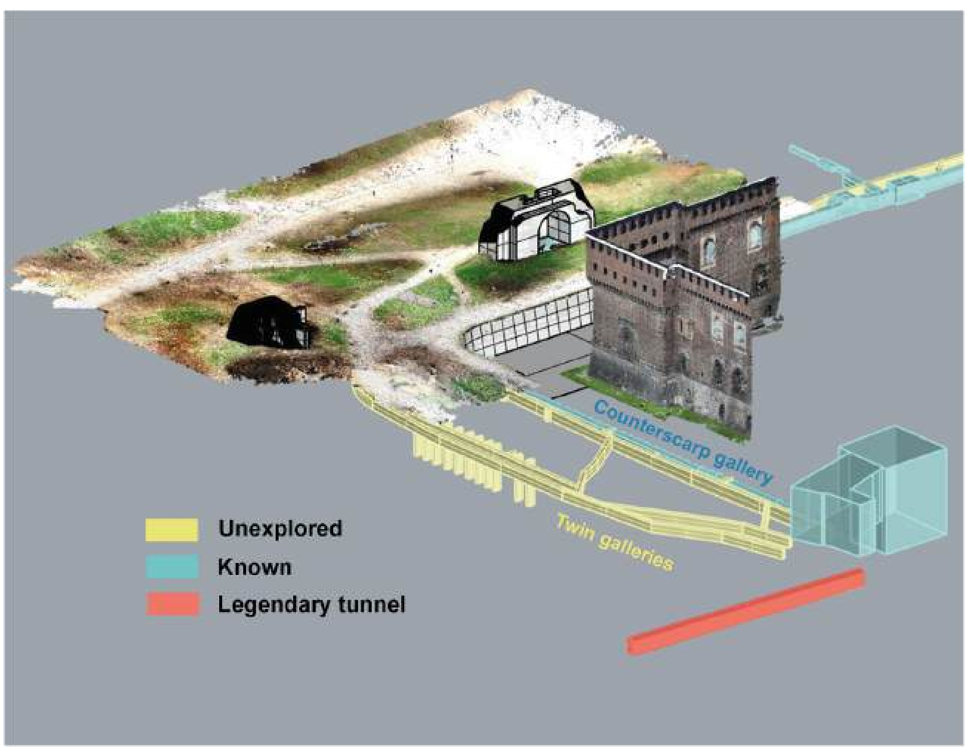

Fig. 16. 3D information model highlighting the complex network of tunnels. The visualization distinguishes between known (blue), unexplored (yellow), and legendary/hypothesized (red) passages, integrated within the architectural point cloud.

heterogeneous sources (from historical documents to point clouds), as well as with direct observations, marks a significant step toward validating long-standing hypotheses and expanding our understanding of the site's hidden architectural features. As demonstrated in Fig. 16, this multidisciplinary synergy transforms the 3D model from a static representation into a dynamic analytical environment. This approach allows for a "transparent" reading of the heritage asset, where different layers of time, historical intuition, and empirical measurement converge to provide a complete and unified vision that would be impossible to achieve through a single discipline alone.

However, the most significant issue highlighted once again by this experience is the essential need for an integrated, multidisciplinary approach in the knowledge, understanding, and management of the built heritage. This approach must encompass disciplines ranging from historical and archival research to modern geomatic surveying and geophysical investigations. This approach allows for a "transparent" reading of the heritage asset, where different layers of time, historical intuition, and empirical measurement converge to provide a complete and unified vision that would be impossible to achieve through a single discipline alone.

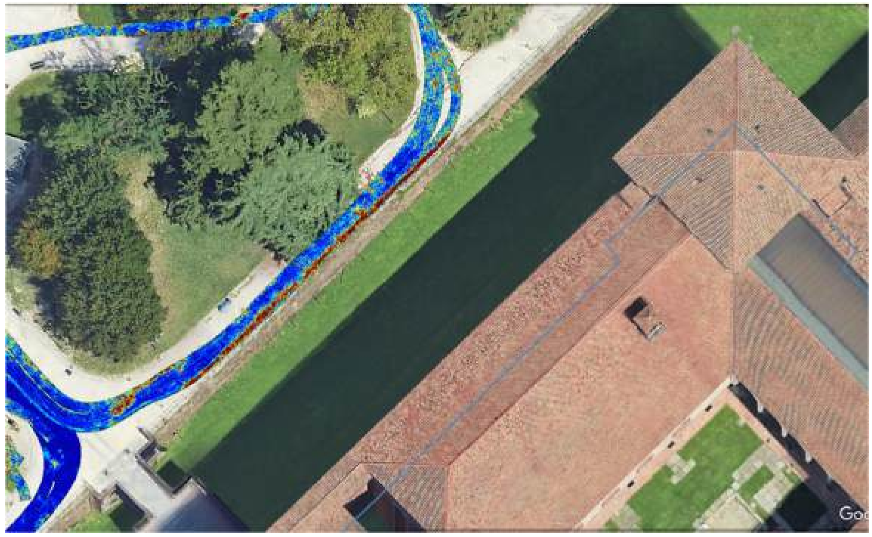

Fig. 17. 3D GPR data view of the counterscarp and "twin" galleries.

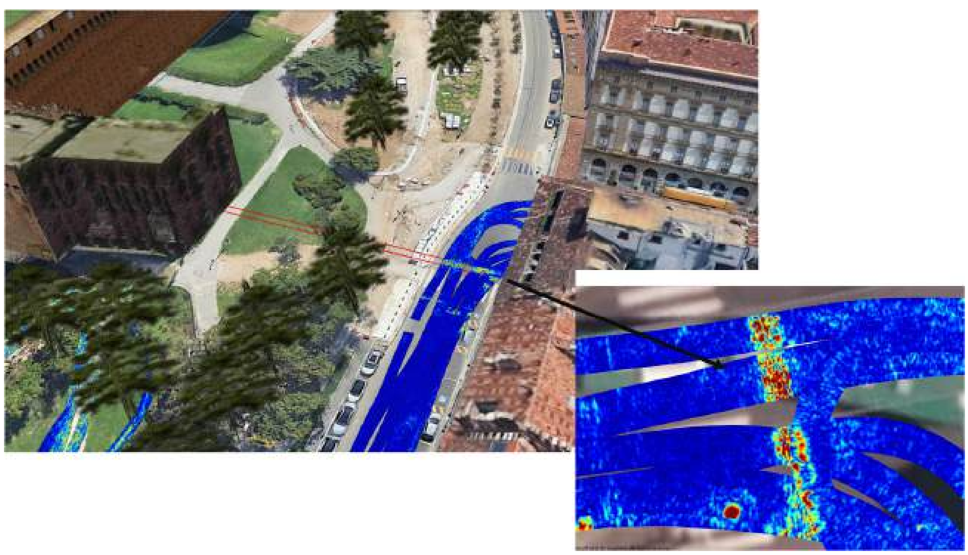

Fig. 18. 3D GPR data view of the underground tunnel leading toward the Santa Maria delle Grazie complex.

To contextualize these discoveries within the modern urban fabric, the final subterranean networks were rendered in 3D over a satellite imagery background. Specifically, Fig. 17 shows the counterscarp gallery and the still inaccessible one that runs parallel to it. In the depth slice, a connecting tunnel between them can also be seen. Similarly, Fig. 18 showcases the 3D view of the legendary underground tunnel leading toward the Santa Maria delle Grazie complex. Overlaying these 3D geophysical results onto satellite data bridges the gap between historical subsurface infrastructure and current urban space, providing a highly effective tool for future research and cultural dissemination.

However, the most significant issue highlighted once again by this experience is the essential need for an integrated, multidisciplinary approach. As a future development of this research, a key perspective involves the digital reconstruction of the newly identified subterranean environments via rendering and synthetic point clouds. By converting the volumetric GPR anomalies into digital architectural geometries, these hidden spaces can be seamlessly merged with the existing lidar and geomatic datasets. This integration will ultimately deliver a unified, high-fidelity 3D digital model of the entire subterranean tunnel network, completing the digital twin of the fortress.

CRediT authorship contribution statement

Maurizio Porcu: Writing – original draft. **Francesca Biolo:** Writing – original draft. **Franco Guzzetti:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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