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Conservation and Enhancement of the Pietrabbondante Archaeological Site between History, Geology and Emerging Crowd-Based Digital Technologies

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Abstract: Attention to the condition assessment and conservation of cultural heritage is increasing due to growing sensitivity to the preservation of the built and natural environment and awareness of the risks associated with natural hazards. In this context, a comprehensive approach to the conservation and valorization of cultural heritage requires the combined action of different skills to achieve reliable assessment of the conditions of valuable assets and sites based on qualitative and quantitative indicators. This paper explores the issues of conservation and sustainable management of archaeological sites, considering humanistic and technical aspects. It reviews the current rules and practices concerning the maintenance and administration of archaeological heritage and outlines the implementation of a novel procedure, based on low-cost tools, to assess and describe the current condition of archaeological assets. Specific attention is paid to the interaction between experts and researchers operating in both humanistic and technical fields and to the knowledge and data contribution available on modern web-based platforms to implement reliable and low-cost data acquisition for the development of worthwhile plans for the conservation and enhancement of cultural heritage. The Samnite complex of Pietrabbondante, Molise, South Italy, is employed to apply and check the proposed tools in the real world.

Keywords: crowdsource images; low-cost data acquisition; maintenance plan; e-conservation; virtual field survey

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1. Introduction

Many areas of Europe are note for the presence of widespread features that over time have acquired great significance in modern societies, becoming part of our cultural heritage. This heritage is made up of all movable and immovable assets that have artistic, historical, and archaeological value and, as such, they need appropriate protection so that their duration can be ensured and cultural development can be promoted [1].

Archaeological assets represent a specific category of cultural heritage; these assets include all the artefacts produced «in a certain historically concluded phase of human civilization» [2], subsequently subjected to alteration and damage caused by time and natural hazards. These assets are exposed to various natural and anthropic hazards, as well as risks related to intrinsic and specific vulnerabilities [2–4]. Consequently, prevention and risk assessment have become key issues, especially in Italy, where archaeological areas and ancient monuments are widely present [5–10]. Several national and international recommendations [11–14] and guidelines [15,16] are issued and continuously updated by the relevant authorities with the aim of incorporating knowledge acquired and outlining an optimal approach to assess the current condition of assets and to define reliable protection measures. The knowledge, protection and valorization of major cultural heritage areas are generally multidisciplinary and based on diverse and/or combined approaches related to different temporal and spatial scales. These analyses aim to understand the natural and anthropic processes responsible for the current state of both the assets and the surrounding urban and rural landscape.

The range of hazards to be considered is wide; in Italy, among natural phenomena, the main causes of disturbance and destruction of cultural heritage areas are floods, landslides, and earthquakes. Their destructive capacity is generally associated with extraordinary rapidity over a large territory. In addition, slow-moving landslides or localized landslides may also gravely damage ancient monuments or archaeological sites [17]. Therefore, joint examination of the geological/geotechnical model of the area and the behavioral and mechanical model of the built environment facilitates and supports a clear understanding of the current state of the historical artefacts and their preservation.

Many studies have proposed procedures and methodologies for identifying and estimating geological and geotechnical factors affecting the state of monumental and archaeological sites [5,18–20], but the most critical aspects are related to the identification of the size of the area surrounding the cultural site that is representative of the engineering geological model of the territory, especially in multiple hazard conditions [5,9].

The definition of hazard zoning depends on the available dataset and requires different approaches related to the specific natural phenomena [21]. With regard to slope dynamics, it is important to base the hazard analysis on an effective landslide inventory and to select the most functional approach (heuristic, statistical or deterministic) [22,23] (and references therein). Obviously, the landslide inventory derives from historical studies, geological, geomorphological, hydrogeological, and geotechnical information combined with field observations and investigations. The acquisition and the elaboration of data, as well as the validation of the process, should be implemented by means of remote sensing, geographical information systems [6,24] and web mapping platforms [25,26].

The understanding of the geological and geotechnical features of an area, combined with the planning of maintenance and conservation measures for the artefacts and preventive assessment of the risks to which they are exposed, facilitates the definition of conservation and management plans [27–31] aimed at preserving archaeological assets and sites. In this context, new methodologies for preventive conservation [32] have been developed starting from European conservation experiences, i.e., Monumentenwacht [33], Monumentenwacht Vlaanderen [34], Monumentendienst [35], and Maintain our Heritage [36]. At the same time, management plans have been developed to identify objectives and strategies to be implemented in order to preserve the heritage [37–39] and its cultural value [40].

The preservation and enhancement of cultural heritage could be properly pursued by adopting procedures that support the management plans and simplify their phases through the application of new technology. Currently, the management plans developed for the World Heritage List are based on information systems that provide actions and strategies that serve to preserve the asset and its values over time by comparing information from different databases [39,41]. Great advantages can be obtained from the innovations offered by crowd-sensing systems and by the Internet of Things (IoT). The technological advances achieved in recent years, both in the information and communication field and in the construction field, in particular in architecture and structural engineering, have facilitated the development of new knowledge and digital models representing cultural heritage. The development of complex informative systems for knowledge dissemination is encouraged, on the one hand, by the correlation between traditional and innovative approaches based on digital technologies and information available on the World Wide Web, increasing the community participation and engagement [42], and on the other by the correlation between qualitative and quantitative information. In addition, the availability of complex informative systems and the IoT paradigms can support decision-making processes by identifying when and how to intervene according to the most appropriate strategies based on the priorities identified by the system [43–45].

The present paper is firmly founded on established knowledge in the field of architecture and archaeology and describes a low-cost data acquisition process designed in order to correlate and share relevant information associated with the implementation of a digital management plan. The proposed procedure is the result of an interdisciplinary approach to the assessment of the archaeological site of Pietrabbondante, a municipality in Molise Region (south Italy), that is still subject to analysis and excavation activities [46]. This critical analysis aims to identify appropriate methodologies and digital tools for supporting the implementation of digital management plans through the future development of a complex informative system integrated and interconnected with the network.

The paper is organized as follows: Section 2 deals with the analysis of the current approaches and available digital tools to develop a procedure and a low-cost tool for the digital management plan and the growth of the heritage community. Section 3 describe the main features of the archaeological site of Pietrabbondante, South Italy, which has been adopted as a testing and validation area; certain details regarding its historical and architectural characteristics along with an overview of the site from a geological and geotechnical viewpoint are given. It also presents some considerations on the results obtained from investigation of the archaeological site are in order to support and facilitate the development of a digital management plan based on collaboration between public organizations, research institutions and the wider community. Finally, Sections 4 and 5 provide discussions and final remarks.

2. Toward an Integrated System for Implementing Digital Plans for the Maintenance and Management of the Archaeological Heritage

The conservation and enhancement of archaeological heritage is a complex task due to the various aspects to be considered to reach these goals. Indeed in the past, the methodological dualism between historical and technical-scientific knowledge often gave rise to inappropriate interventions irrespective of the assets' value, for example invasive interventions involving the use of modern materials and structures that jeopardized the assets' authenticity [47]. As a consequence, the need to implement strategies to prevent the occurrence of losses and casualties was expressed by promoting maintenance activities, such as the challenging maintenance plans developed to protect Italian archaeological sites [28,39], and implementing specific management plans. The latter are effective tools for identifying the objectives and strategies to guarantee, over time, the conservation and enhancement of the heritage and its cultural values [40,48].

New methodological approaches have been recently proposed for implementing conservation and management plans, although they are not specific for archaeological sites but for large built areas such as historical centers [41,43,44]. These approaches have been developed from the knowledge and methodologies already available and are able to fill the existing gaps by promoting the application of new information technologies in the built heritage conservation field. Indeed, the spread of digital technologies and crowdsensing paradigms have encouraged novel approaches to the knowledge and assessment of the current condition of built heritage [49–53]. At the same time, the information available thanks to digitization and/or community contribution [54–56] facilitates the development of complex informative systems [57–60]. These systems link digital models to databases related to bibliographic information, images collected in situ or online, data concerning history, materials, construction techniques and state of preservation supporting the processes of knowledge and conservation of cultural heritage, and specifically of archaeological heritage.

Based on these assumptions, the research is aimed at evaluating the advantages deriving from the integration of traditional methodologies with those based on the use of novel technologies for developing an operational procedure for implementing a novel informative system intended for the conservation and management of built heritage.

The different phases necessary for employment of the above mentioned informative system were hence defined, also identifying an expeditious tool, the SUNDAE Catalogue v.1.0 (Section 2.1), that fits the requirements of a multi-layer tool for the acquisition of information through the involvement of the community, supporting the documentation process. Previous experiences in the study and analysis of cultural heritage have shown that an interdisciplinary and systemic approach, coherent with the recommendations and directives mentioned above [11–16], is crucial for developing appropriate complex informative systems. Heterogeneous data related to history, archaeology, architecture and geology are collected through dynamic and open cooperation between different experts with a multi-scale and multi-level perspective. These data have to be processed and combined in order to adequately document and describe the investigated area and artefact and define the structure of the informative system.

Therefore, the starting point for designing such systems is knowledge of the site and artefact, in order to have qualitative and quantitative data significant for conservation and management. The information about the location and natural hazards, historical-constructive evolution, material and construction techniques need to be integrated with the dimensional data. In this way, the original elements plus those added, the components that characterize the structural system, the geological and geotechnical features, and, lastly, the nature and the evolution of degradation and damage phenomena can be properly identified [61,62].

The information recovered during the earlier phase are elaborated and digitized within the database [52,62,63] to facilitate their management and make them available at different levels, namely to researchers and technicians involved in the analysis and management processes and to a wider community interested in knowledge of the artefact.

In addition, the acquired geometrical and dimensional data are used to implement the digital replica of the investigated area and artefact. The virtual models are the result of processing data acquired through planned survey campaigns, i.e., Unmanned Aerial Vehicle photogrammetry [64–66], or those made available by the community through dedicated platforms [51–53,67,68]. Therefore, these models should be enriched from a semantic point of view [69–72].

Finally, the virtual replica obtained should be linked to a system for collection and analysis of data provided by real-time monitoring of environmental conditions and the state of health of the artefact [73] for the effective implementation of the integrated system. In such a way, interventions on cultural heritage can be prioritized [74], empowering conservation action by using a complex information system resulting from the correlation between the digital replica and the monitoring system. A helpful interaction of this sort can guide effective and non-invasive interventions at the right time [44,45]. To achieve such a goal, the informative system must interact with different territorial management systems fully exploiting the Digital Twin of the heritage and the potential offered by the IoT [45,75–77]. As a result, the time required to define the preservation and enhancement strategies for built heritage is reduced by using a single information system, based on shared knowledge and a unified vision of the object of interest.

The following section provides additional details on the suggested expeditious tool for data acquisition based on crowdsourcing, while the application to an explanatory case of an archaeological site located in Inner Areas of Molise region, in south Italy, gives an opportunity to test and validate the main phases of the proposed procedure for the creation of the complex informative system.

2.1. The SUNDAE Catalogue v.1.0

The need to make the cultural heritage preservation and management process more efficient and to reduce the time required to define suitable strategies has led to exploring the benefits of the community involvement in knowledge and preservation of archaeological sites, thus exploiting the potentiality of crowdsourcing [54,56,78]. Some experimentation conducted by the authors on architectural heritage [52,53] has shown that when community participation cannot be achieved directly through specialized platforms, knowledge and preservation processes can benefit from crowd-based data by cataloguing information retrieved on blogs, social networks, web-based video posting and sharing platforms (e.g., YouTube) or open-access web-mapping systems (e.g., Google Maps). This process led to the implementation of the SUrvey and CoNDition AssessmEnt—SUNDAE—catalogue (Figure 1), which enables the collection of crowd-based images and provides a critical assessment of the conservation condition of an investigated property [52,53]. The catalogue form was developed based on the F form provided by the Central Institute for Catalogue and Documentation (the Italian ICCD) for the inventory and cataloguing of photographs [79]. The images collected on the web are identified through a univocal code and associated with information that permits the identification of the property's location, the date and authors of photographs, as well as the acquisition of general information about the asset examined and the cultural period of reference. The chronological ordering and analysis of the images collected within the catalogue, as already tested for the Haghpat Monastery in Armenia and the *Santa Maria della Strada* Church in Molise [52,53], permit the identification of degradation and/or damage phenomena and an understanding of their evolution over time.

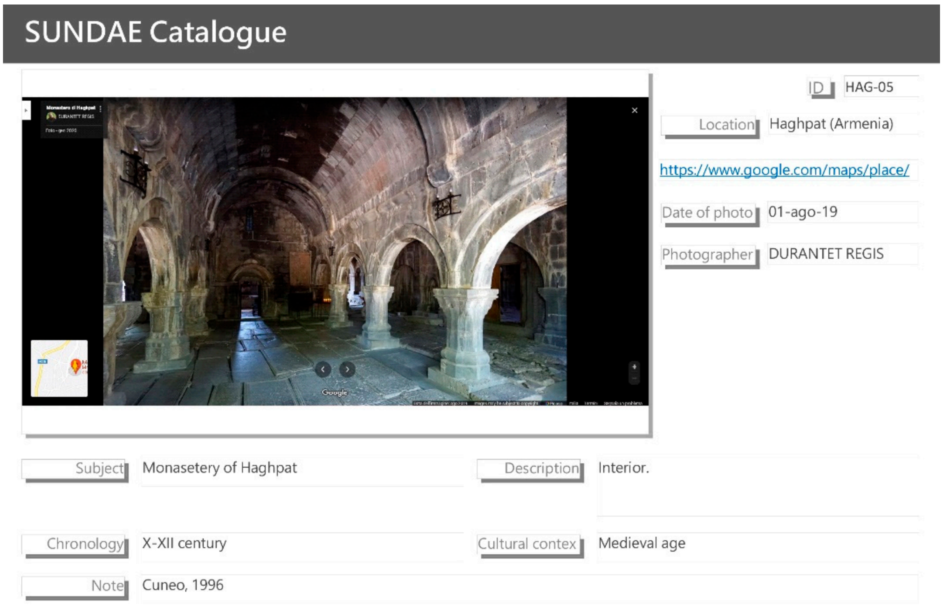

Figure 1. Example of SUNDAE catalogue form. Application to the Monastery of Haghpat in Armenia.

However, the SUNDAE Catalogue is not appropriate for community use, and, therefore, does not contribute to the growth and development of the heritage community, as defined within the Faro Convention [42].

From this perspective, and with the aim of supporting institutions in the enhancement and fruition of archaeological heritage, version 1.0 of the SUNDAE Catalogue was developed. An online module, which enables the gathering of data provided by the local community directly in the cloud, was used to implement this version. Different sections have been created within the module to collect specific information on the examined area and images related to the whole archaeological area and the single identified artefacts (Figure 2). A section on the geological setting has been added compared with the previous version. In particular, this part collects geological reports and geographical information related to location of archaeological sites (*Location* and *Geographical Coordinates fields*). The World Geodetic System (WGS84) is the reference coordinate system and links to the National Environmental Information System are also available. Thus, the consultation and integration of data, maps, reports, photos, videos and documents from the national platforms and databases related to geology, soil, water, climate, weather and natural hazards to which the area is exposed are made easier (Figure 3).

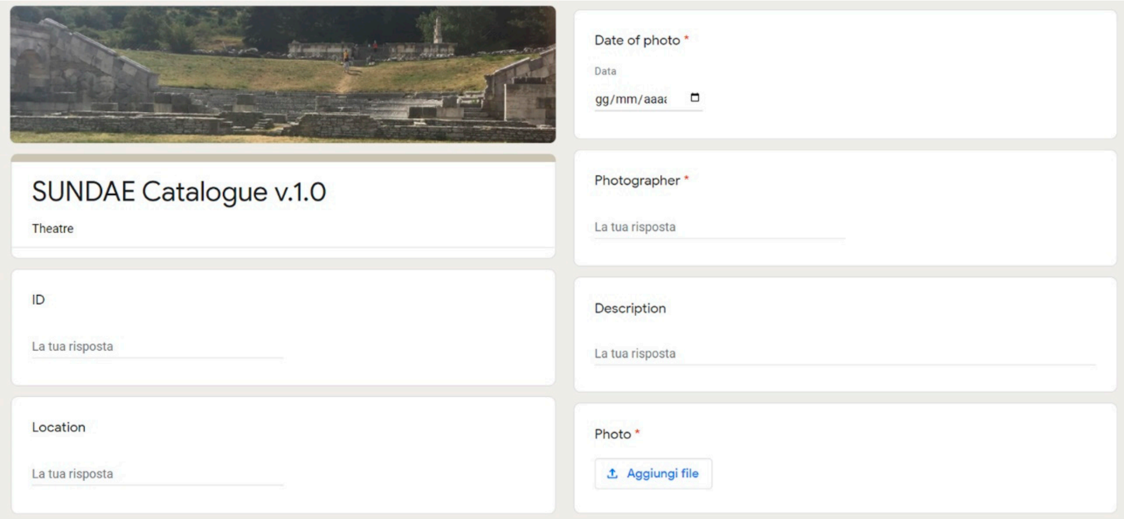

Figure 2. The online module of SUNDAE Catalogue v.1.0.

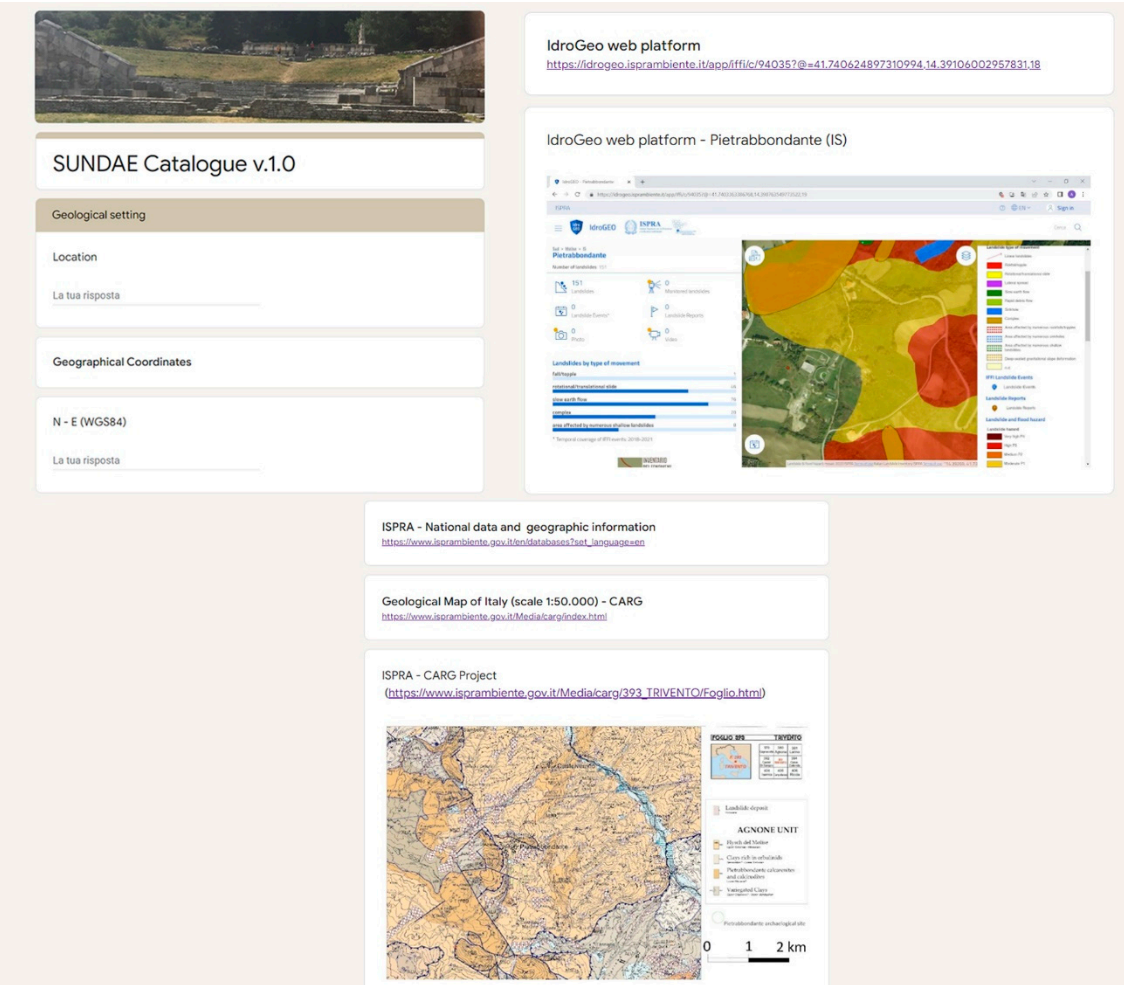

Figure 3. The SUNDAE Catalogue v.1.0: the section of Geological setting.

Furthermore, the images collected within the SUNDAE Catalogue v.1.0 can be reprocessed to complete, through automated procedures, the previously compiled catalogue. This provides a broader database that facilitates the analyses concerning the artefact's state of conservation. At the same time, the possibilities offered by automatic procedures and the interoperability of systems enable the implementation of a multi-level platform that integrates the data coming from global platforms with those generated by local networks and systems, thus supporting the decision-making process of the interventions.

In addition, the photographs within the cloud can be used to update the virtual models of the archaeological area or single artefact. Lastly, it should be pointed out that this module can be easily linked and compiled within virtual reconstructions, such as Virtual Tours and parametric models [71,80], demonstrating its effectiveness in use within different solutions and its capacity for compilation at different times.

3. Crowd Based Data Collection in the Inner Areas, an Explanatory Test Case

The tasks of conservation and enhancement of cultural heritage are more complex for the Inner Areas of Italy. These Areas are characterized by the weakening of the production system due to the abandonment of agricultural production and the presence of historical and artistic assets which are poorly valued and known, but could represent the main source for economic, social and environmental development of these areas [81].

The cultural heritage of these areas is evidence of the past that needs to be safeguarded by collaborative action between a number of institutions and entities, as indicated by the National Strategy for the Inner Areas [82].

The purpose is to enhance the social and economical improvement of many areas located in the Southern Apennines, where certain institutional actors, like the University of Molise and the National Research Council operate.

The site of Pietrabbondante is one of the successful examples of joint activities aimed at developing and implementing conservation and management plans via a multidisciplinary approach. Various knowledge is involved, to ensure that the archaeological area and its artefacts will be preserved for the future by identifying the most suitable methodological choices for the research and assessments to be carried out and for enhancement strategies [83–85] and as a component in the development of complex informative systems.

3.1. The Site of Pietrabbondante

The archaeological site of Pietrabbondante, a municipality in the Molise region, was analyzed to identify and test approaches and tools that facilitate the conservation of diffuse heritage in Italian Inner Areas, on the one hand, and community participation in knowledge and protection processes, on the other.

The site is important evidence of the Samnite people in the Molise region (Figure 4). It currently investigated by means of excavation activities and technical studies aimed at assessing the area's stability conditions and analyzing the landslide processes that caused its decline and the alterations and deformations detected on the structural remains brought to light.

The Pietrabbondante complex was active between the 5th and 1st centuries BC as the main religious and public site of the Samnites Pentri people and it was abandoned during the 2nd century AD [86–88]. The Second Punic War and the passage through the area of Hannibal's Carthaginian army in 217 BC probably resulted in the destruction of several constructions, so the rebuilding of the site might have started in the 2nd century BC.

Figure 4. Location of Molise Region and the archaeological site of Pietrabbondante, showing the timescale of excavation of the archaeological evidence rediscover.

In the 19th century, the Bourbons started a number of archaeological excavations that revealed the ancient theatre (Figure 5) and the site's smaller temple (Temple A) (Figure 6). Excavation activities have not been continuous over the years, but after the Bourbon excavations the site provoked the interest of researchers, historians and archaeologists. In 1959, important works was conducted by Italo Gismondi on the archaeological evidence, which also led to the discovery of the great temple (Temple B) [89] (Figure 7).

Figure 5. The ancient theatre, with Temple B and Mount Saraceno in the background (photo by authors).

Figure 6. Temple A (photo by authors).

Figure 7. Temple B (photo by authors).

New excavation activities were begun in 2002 by Adriano La Regina and still continue today, bringing to light the splendid remains of this huge ancient complex [86–88].

The Samnite culture and the historical events related to the site were rediscovered thanks to this excavation work (Figure 4), which has highlighted the settlement's important role from its construction to its decline [46,89].

During these activities, various stratified deposits have yielded numerous artefacts (coins, items related to war, religious objects such as bronze statues, votive slabs), demonstrating the importance and the public and cult structures present [86,87,90,91]. However, the most important evidence is represented by the buildings erected by the Samnites, which illustrate their constructive abilities and knowledge [92,93]. In particular, as a result of these activities, the following monumental buildings have been investigated and uncovered:

- the *Sacello* of the Eastern Sanctuary, characterized by three areas standing in line [46]. It was used until the late Republican era, and then desacralized and abandoned due to the suppression of pagan cults and the demolition of their temples in 406 AD;
- the *aerarium* and small *stoà*, built in the eastern area of the site in the last years of the 3rd century BC and characterized by three rooms that opening onto a portico used to store worshippers' offerings;
- the *tabernae*, located on two parallel terraces between temples B and A. It was first destroyed by lightning during the 2nd century BC and then by a fire in the 4th century AD.

Among the significant structures revealed by excavations, the theatre and the *domus publica* are of particular interest for their structural and architectural features.

The construction of the theatre dates back to the late 2nd and early 1st century BC. The theatre was used both for theatrical performances and political meetings; it is similar to the *Odeion* of Pompeii in its architectural layout and sculptural decoration, as revealed by comparison of their structure configurations and the marked affinity of their artistic and architectural decorations (Figures 8 and 9) [94].

Figure 8. The theatre of Pietrabbondante: (**a**) the *cavea*; (**b**) front and (**c**) back side of the left *parados* (photos by authors).

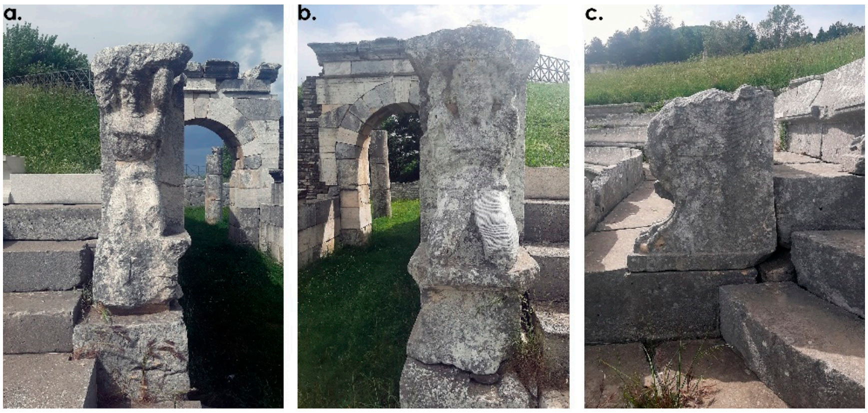

Figure 9. Pietrabbondante Theatre decorations: (**a**,**b**) Telamon and (**c**) griffin (photos by authors).

The *domus publica* dates back to the 2nd century BC (Figure 10); it was discovered in the western side of the area in 2002 and was brought to light by excavation activities in 2009 [46,95]. The building covers a large part of a terrace bordered upslope by the hillside and on its outer side by a stone wall against the earth beyond. The *domus* is a Roman-Italian house of the late Republican age type, renovating some spaces for public and sacred purposes [86].

Figure 10. View of the *domus publica* (photo by: GEOTURISMO natural Heritage, 2015—https://www.facebook.com/geoturismo.sannio/photos/1627342124214162, accessed on 10 December 2020).

A brief analysis of the main geological and geotechnical features, based on the available technical documentation, and the phenomena that threaten this archaeological site are provided in the next section.

3.2. An Overview of the Geological Characteristics of the Archaeological Site

The municipality of Pietrabbondante is located in the north-western sector of the Molise Region (South Italy), which is characterized by calciturbidites enriched with silici-clastic deposits composed of clay and marly clay interbedded with sandstone [96]. With regard to the complex evolution of the fault and thrust Southern Apennine chain [97–100], the Oligocene-Miocene succession involves the Molise basin formations, namely the Agnone Unit [101,102] (and references therein).

The archaeological site is located along the south-eastern slope of Mt. Saraceno at an altitude between 1000 and 950 m a.s.l. The slope gradient is about 12%.

In this area crops out the upper member of the Agnone Unit, known as the "Flysch del Molise" (Figure 11). This Upper Miocene flysch consists of synorogenic arenaceous-clayey sediments. Grey and brown pelites, with a maximum thickness of 40–50 cm, alternate with grey-yellowish micaceous sandstones. The central part of the succession includes coarse to medium-grained sandstones, sometimes in massive beds containing centimetric silty-clayey layers [101].

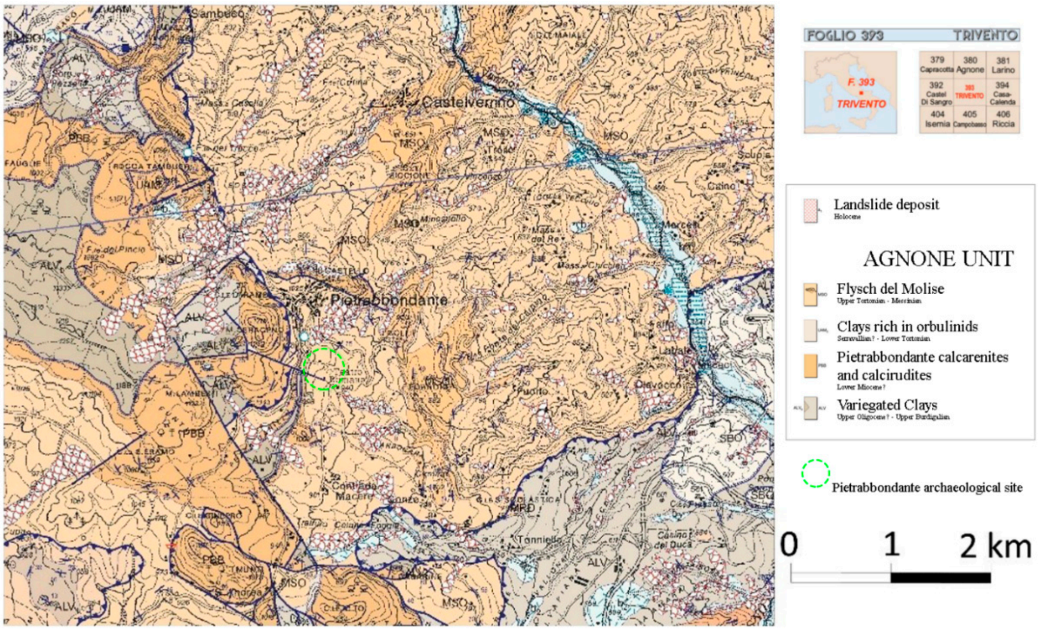

Figure 11. Excerpt from Sheet 393—Geological Map of Italy in scale 1:50,000 (ISPRA, 2010).

Currently, the main morpho-evolutional elements are the many active gravitational phenomena present, often linked with stream erosion. More in general, the landslide phenomena noticed, both quiescent and active, include soil creeps, solifluctions and complex movements (IFFI Project) [103] (Figure 12). The climate is temperate oceanic; the annual temperature is about 10 °C and the annual rainfall is about 1090 mm on average.

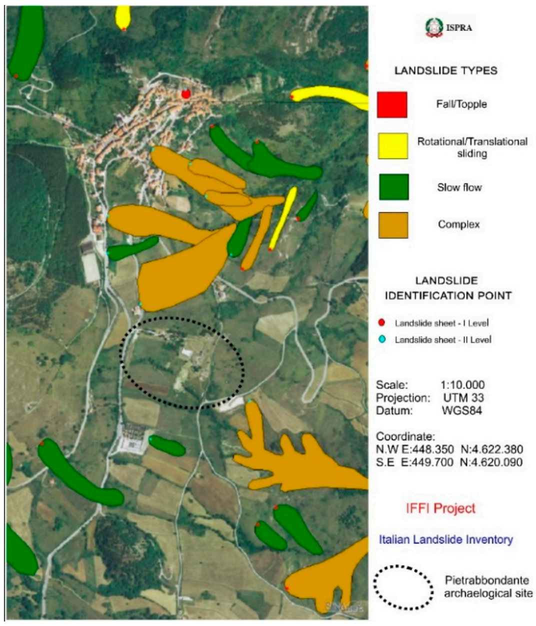

Figure 12. Main active gravitational phenomena recognized in the Pietrabbondante area (adapted from IFFI Project).

The geotechnical in situ and laboratory tests performed in the context of the archaeological site [104,105] consist of five boreholes drilled in the depth range 20 to 30 m and one Down-hole test (DH), plus laboratory tests (grain size distribution analysis, Atterberg limits tests, UU and CU triaxial tests, direct shear tests and unconfined compressive tests) on eight undisturbed soil specimens, selected in the depth range 1.5 to 20.5 m. These investigations, carried out along the slope which characterizes the archaeological area (Figure 13), were integrated and analyzed considering the geotechnical in situ and laboratory tests implemented for the territorial restoration plan of the Pietrabbondante municipality.

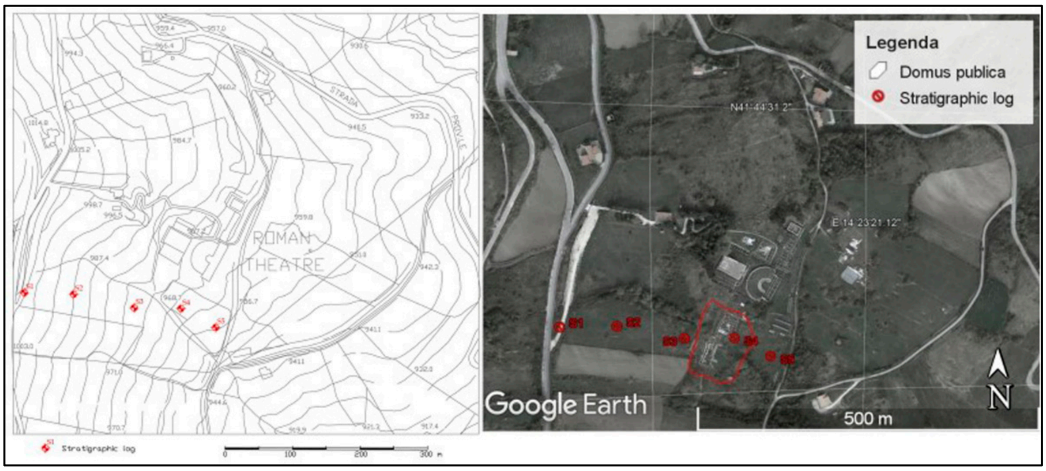

Figure 13. Location of boreholes.

The re-elaboration and interpretation of available datasets provide an overview of the lithostratigraphical profile of the slope over which the archaeological structures are spread.

Review of the collected geological data indicated the presence of three homogeneous layers from the ground-surface downward (Figure 14):

- Layer A: Chaotic colluvial deposits, composed of havana brown clayey silts containing plant residues and occasional calcarenitic fragments. Thickness: 0.5–1.6 m;
- Layer B: Weathered and reworked deposits due to creep and solifluction processes. These consist of havana brown and grey silty clays characterized by a weak scaly/schistose structure. These deposits contain organic matter as well as occasional marly and calcarenitic fragments and are often iron-oxidated and decalcified. Thickness: 1.7–4.6 m;
- Layer C: Grey scaly silty clays interbedded with centimetric to decametric marly and calcarenite levels. The top of the layer is at a depth of 2.5–5.8 m below the ground surface.

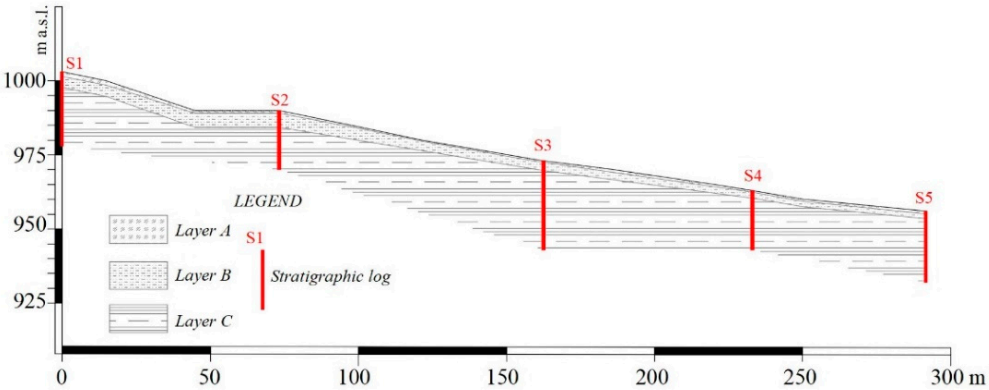

Figure 14. Lithostratigraphical section of the slope on which the archaeological structures are spread.

These lithostratigraphical layers matched the same number of lithotechnical levels. Tables 1 and 2 contain the relevant geotechnical data, in particular the main information obtained from the aforementioned five stratigraphic investigation logs and laboratory tests on the associated undisturbed soil samples.

Table 1. Summary of soil layer particle-size distribution.

Stratigraphic Log	Sample	Depth [m]	Layer	Particle-Size Distribution			
				Gravel [%]	Sand [%]	Silt [%]	Clay [%]
S1	S1C2	12.30–12.80	C	0.0	7.2	55.5	37.3
S2	S2C1	1.80–2.30	B	0.0	14.8	57.9	27.3
	S2C2	5–5.50	B	0.0	14.6	59.2	26.2
S3	S3C1	1.5–2	B	0.0	7.8	61.6	30.6
	S3C2	4.5–5	C	0.0	6.4	52.9	40.7
S5	S5C1	1.5–2	B	0.0	7.2	54.2	38.6
	S5C2	12–12.5	C	0.0	11.4	48.5	40.1
	S5C3	20–20.5	C	0.0	7.8	55.5	36.7

Table 2. Summary of soil layer relevant physical parameters.

Stratigraphic Log	Sample	Consistency Limits				Water Content w [%]	Degree of Saturation S [%]	Porosity *n* [%]
		Liquid Limit LL [%]	Plastic Limit PL [%]	Plasticity Index PI [%]	Consistency Index CI			
S1	S1C2	54.0	20.0	34.0	1.13	15.64	84.86	33.31
S2	S2C1	33.0	18.0	15.0	0.82	20.71	84.84	39.64
	S2C2	35.0	14.0	21.0	0.70	20.33	96.35	36.12
S3	S3C1	47.0	18.0	29.0	0.74	25.59	100.00	40.43
	S3C2	47.0	11.0	32.0	0.77	18.27	79.55	38.45
S5	S5C1	48.0	14.0	34.0	0.87	18.35	84.01	37.10
	S5C2	46.0	11.0	35.0	0.74	20.10	80.97	40.31
	S5C3	46.0	17.0	29.0	1.15	12.64	76.60	31.06

The lithotechnical levels identified were composed of fine-grained soils, more precisely silts and clays (Low plasticity Clays-CL and High plasticity Clays-CH). From the ground-surface downward (proceeding from layer B to layer C) the plasticity increased and lean clays and fat clays (USCS) were recognized. In addition, the consistency changed from medium to very stiff (Terzaghi classification).

Clearly, the dissimilar properties of the two layers (B and C) can be associated with the weathering and reworking of the more superficial layer B, which was related to creep and solifluction processes.

3.3. Results

As described in the previous sections, the archaeological site is characterized by artefacts with different typological and constructive features and is located in a geologically and geotechnically complex area. The state of preservation of the assets is threatened by several degradation and damage phenomena due to their history and the time elapsed since their excavation. Furthermore, it is worth noting that some elements have been removed and then reused in other historical buildings (e.g., the white marble from Temple B floor was reused in the S. Maria Assunta Church) due to the state of neglect of the area [46].

Analysis of the conservation state of the artefacts was performed starting from the information acquired in situ and data collected through crowdsensing systems, which were organized within the SUNDAE catalogue and then analyzed [52,53].

Degradation and damage phenomena caused by exposure to exogenous factors, stress derived from excavation procedures and previous conservation interventions have been recognized by means of the analysis and correlation of different information. Moreover, the lack of maintenance and the vulnerability of the area in relation to the solifluction processes have also increased its deterioration and degradation state.

Several masonry walls show decay and loss of material and historical mortars, as well as erosion phenomena of decorative surfaces, caused by the effects of wind and water runoff, freeze-thaw cycles and thermal changes. These natural events facilitate the development of several phenomena, such as crusts, biological patinas and efflorescence on surfaces, that can be observed in the theatre *cavea* and in the front of the terraced retaining wall that delimits the so-called "unfinished construction site".

In particular, in the podium of Temple B can be observed stains and crusts caused by the permanence of structures within soil deposits and other materials (Figure 15). A worsening of degradation phenomena can be observed by comparing images of the podium over time, and therefore maintenance and conservation interventions should be planned (Figure 16).

Figure 15. Degradation phenomena on Temple B (photo by authors).

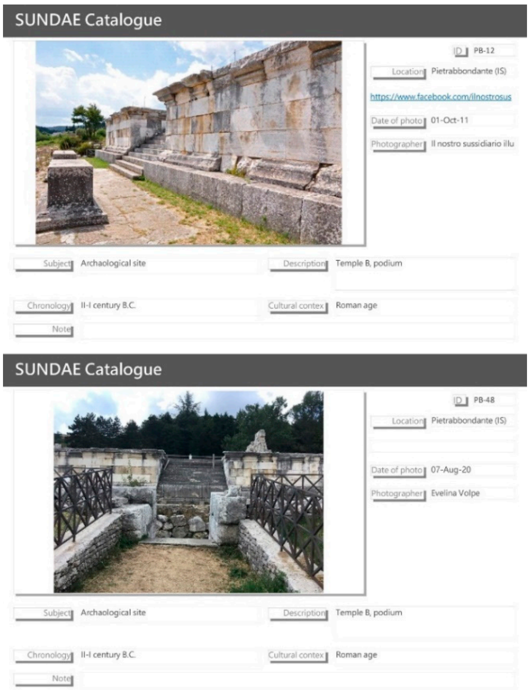

Figure 16. State of conservation of Temple B, comparison between 2011 and 2020.

The possibility of retrieving information on the state of preservation of archaeological sites by comparing images collected in situ with those collected by means of crowdsensing tools (Figure 17) highlights the opportunities arising from the use of such tools. In this way the evolution of degradation and decay phenomena [52,53] can be traced and recorded along with the interventions carried out over time.

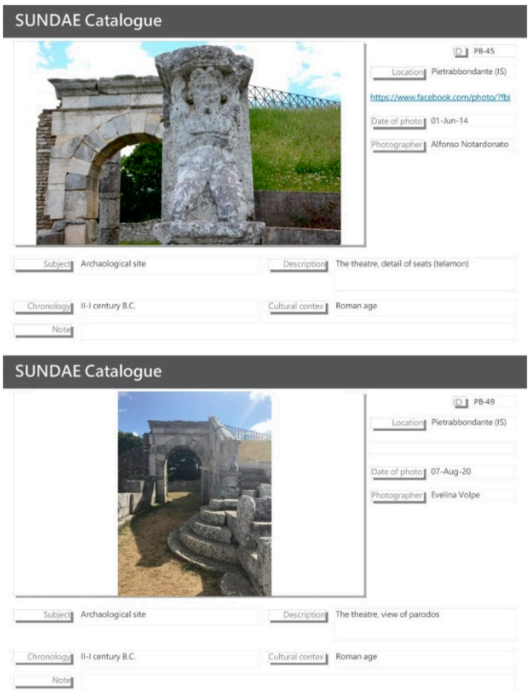

Figure 17. State of conservation of theatre, comparison between 2014 and 2020.

In addition, other decay and degradation phenomena, in particular rotations and deformations, can be detected in some artefact parts, for example in the *cavea* and orchestra space of the theatre and in the northern sector of the archaeological site (Figure 18).

Figure 18. (**a**,**b**) View of deformed shape of the architectural remains (photos by authors).

Specific investigations must be carried out on every single artefact in order to verify its preservation state and the compatibility between ancient and new materials and to identify the most suitable preventive conservation and restoration interventions [27].

Diverse instability phenomena are also visible in the northern area [106]. Signs of alteration of the historical building, due to slow gravitational slope deformations are visible in the *domus* colonnade, as shown in Figure 19. The original alignment of the portico has been lost due to superficial movements of the ground uphill and multiple and differential instabilities of the foundation ground. In this area, a slow but continuous visco-plastic deformation is in progress [93]. This phenomenon became apparent following the opening of new excavation areas and has caused deformation of these areas and the archaeological remains.

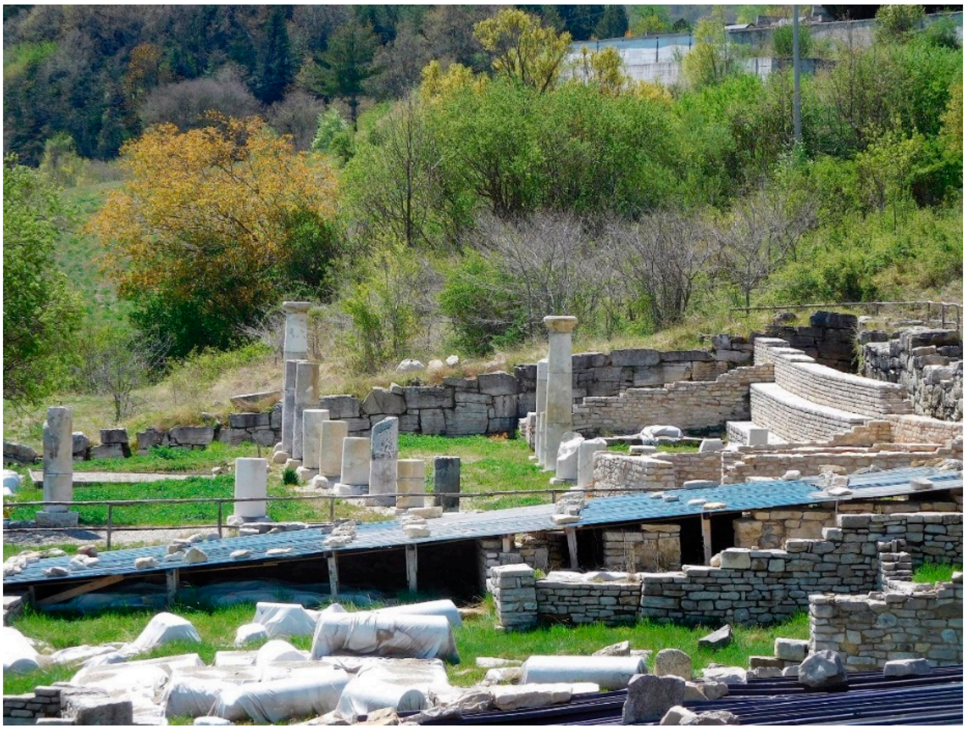

Figure 19. Current state of the *domus publica* colonnade (photo by: Massimiliano Guerriero, 2017—https://www.facebook.com/photo/?fbid=1327113377375715&set=a.358595767560819, accessed on 10 December 2020).

Although quantitative analysis of the geotechnical conditions of the site is beyond the scope of the present paper, the authors are also involved in a more comprehensive study related to the assessment of site stability conditions. In particular, insight into the slow gravitational phenomena that have caused alterations and deformations, both within the *domus* area and in the northern area of the site, represents one of the technical developments of the present study. The overall stability of the area and an assessment of soil deformations constitute a key issue in the Pietrabbondante complex, where archaeological excavations are still in progress.

However, the advantages of crowdsourced video and image processing were exploited to obtain a three-dimensional view of the archaeological site that is useful both for documenting and understanding the area and for evaluating the stability conditions of the site and hydrogeological instability phenomena [51–53].

In particular, the theatre area was recreated by processing a crowdsourced drone video using Agisoft Metashape Professional 1.5.1. (Figure 20).

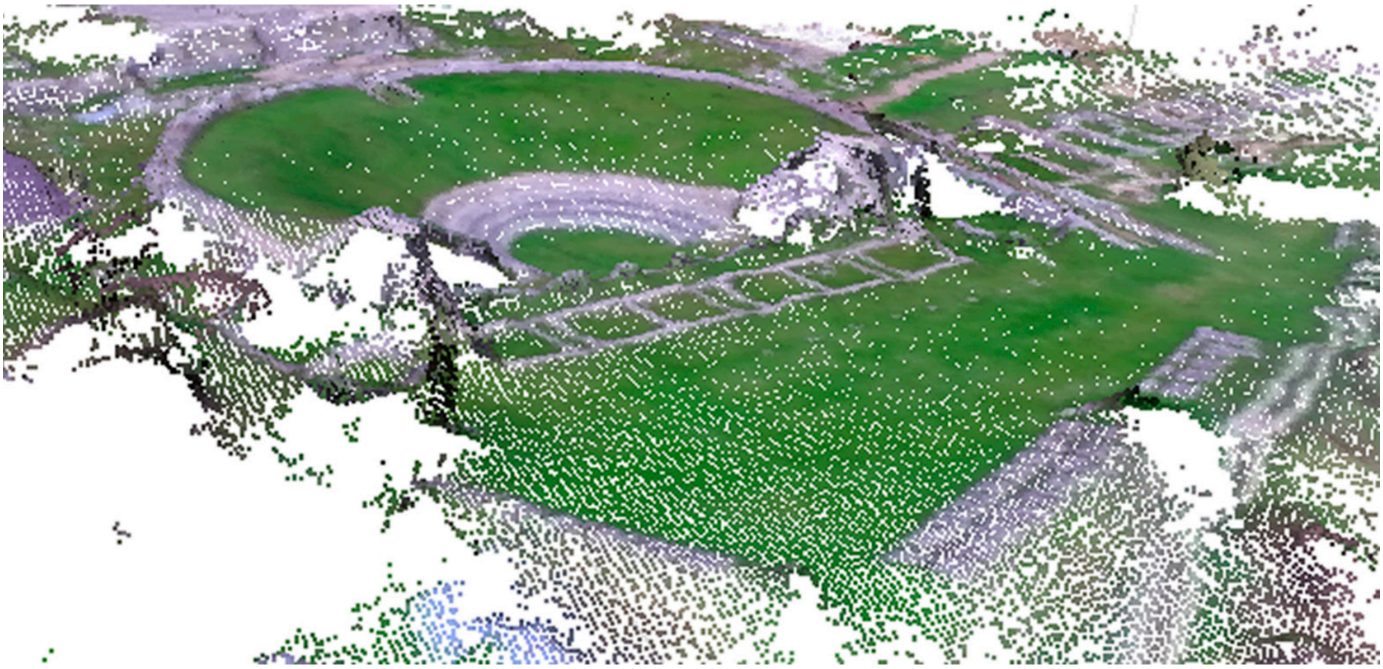

Figure 20. Point cloud from crowd-based video data processing.

The model obtained does not have a high level of detail, but it provides information that can be used in the assessment process of the landslide processes that caused the alterations and deformations found on the artefacts in the archaeological area.

To obtain a model that can be integrated into platforms and tools useful for the management, documentation, knowledge and conservation of cultural heritage, the crowd-based information acquired through compilation of the SUNDAE catalogue was processed for each artefact, or single element, within the archaeological area.

This process delivers sub-models of the investigated area that can be merged to obtain a general model of the site. In particular, a the three-dimensional reconstruction of the left *parodos* of the theatre was implemented. Although few, detailed good quality images of it were collected via the SUNDAE Catalogue. The processing of the crowd-based images within the Agisoft Metashape Professional 1.5.1 software led to a virtual reconstruction of this part of the architectural artefact with a good level of detail (Figure 21).

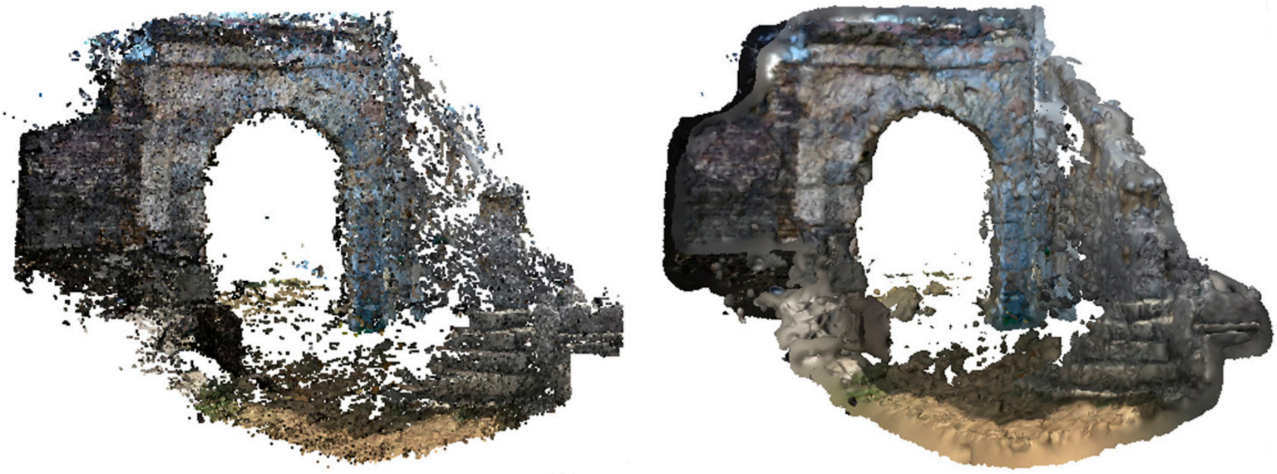

Figure 21. The left *parodos* of the theatre: on the left, dense point cloud 1.5 M points), on the right, 3D mesh model (300 K faces).

4. Discussion

The results obtained, although preliminary, highlight the potentiality of new tools and ways to increase the possibility of sustainable practical management of archaeological heritage. This is especially because the proposed approach allows the involvement of both the authorities in charge of site management and the public. Indeed, the archaeological site of Pietrabbondante was the second most visited cultural site in Molise in 2020 [107], and various theatrical and cultural events that attracted widespread public interest have been held in the theatre in recent years. These circumstances confirm the great value recognized in the Pietrabbondante complex and the reciprocal advantages that may be obtained if management, reception, usability and communication services are improved. The advantages offered by the application of Information and Communication Technologies (ICTs) for built heritage through the future development of a specialized platform that is able to support the management and use of collected documentation [59,108] and to correlate the acquired information, including historical and archival, to virtual and three-dimensional reconstructions [45,109] may thus be exploited in order to properly plan maintenance interventions. For instance, a digital platform like that implemented by the Lombardy, Friuli Venezia Giulia and Veneto Regional Authorities (RAPTOR) [110], with the digitalization of historical archives and other relevant information, would effectively support activities related to the administration of the site.

An updated mapping of the archaeological remains and the hazards at the site can be provided by means of the described methodology; the correlation between the RAPTOR platform and the complex informative system discussed above (see Section 2) would facilitate the planning of interventions to be implemented for conservation and enhancement. In addition, the ICT tools support the communication and effective representation of research results [111,112], facilitating the accessibility of the heritage and contributing to its digital conservation as well as to its enhancement [113]. These goals can be achieved by developing websites and virtual reconstructions that engage and make accessible the site to a wider community, comprising researchers and academics of several disciplines and above all the general public [113,114]. In this context, some interesting activities for involving the community and disseminating information, have already been implemented, through the creation of a virtual reconstruction of the site in its original *facies* accompanied by a narration of the history and culture of the Pentri Samnites [115]. In order to follow and understand the evolution of degradation/disruption phenomena, gamification and visitor engagement processes should be further promoted [116,117], exploiting the advantages of crowdsensing. In this way the set of images can be enlarged along with the others probability of collecting representative photographs of the asset resulting in improved virtual reconstructions supporting the documentation and conservation of the area of interest. At the same time, the impact of community participation in the conservation processes could be increased and the growth of the heritage community [42] facilitated. These objectives can be pursued by using an appropriately planned interactive itinerary to deliver the acquisition of representative photographs of the assets from established points within the same itinerary via the developed online catalogue (SUNDAE Catalogue v1.0), made available by the authorities to visitors to the area.

5. Conclusions

The conservation and fruition of archaeological sites are generally associated with specific and complicated difficulties that are not just technical, since surveillance and maintenance of the assets themselves and the surrounding areas require stable and sufficient resources. In addition, concurrent interdisciplinary work by technical and humanistic actors represents a key phase in safeguarding against natural hazards and specific vulnerabilities that threaten the archaeological area and assets. Based on these considerations, the approach developed also offers also the baseline for an answer to the problems concerning the sites' development and their fruition in time, and thus favors the sustainable economic exploitation of these resources, with clear advantage for the neighboring communities. Indeed, a multidisciplinary approach involving collaboration with local administrations also facilitates the conservation, management and enhancement of cultural heritage, especially when it employs innovative solutions for the participatory involvement of visitors.

These complex topics have been analyzed and discussed by using as an outstanding example the inestimable archaeological site of Pietrabbondante, which represents a unique case; on this minor site in the south of Italy, extraordinary historical and cultural remains of the Samnites are in harmony with the urban landscape and environmental heritage. The management and exploitation of the site clearly appear challenging tasks, since several issues relating to the area's geological and geotechnical features and the conservation state of artefacts have been found. Moreover, the services currently available are not able to support the proper enhancement of the site, making it difficult to use from a cultural perspective. However, in order to develop a suitable management plan such as previously described, further analyses and assessments must be carried out.

In such a context, a twofold contribution of the paper can be pointed out: first, it represents one of the early studies carried out on the Pietrabbondante site that includes also technical and scientific aspects associated with the development and enhancement of the cultural and environmental assets of the site, belonging to the Molise Region Inner Areas; then, this work reports an effort towards the implementation of a low-cost data acquisition platform to feed a multidisciplinary and participatory investigation aimed at designing optimal strategies and tools for sustainable preservation, maintenance and protection of valuable archaeological assets.

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