DEGRADATION OF HISTORIC MASONRY BY ANALYTICAL AND DIGITAL PHOTOGRAMMETRY: A QUANTITATIVE ANALYSIS

Maria Grazia D'Urso[1], Constantino Luis Marino[2], Joel Aldrighettoni[3]

[1]Department of Engineering and Applied Sciences, University of Bergamo, Viale G. Marconi, 5 Dalmine (BG), 24044, Italy - mariagrazia.durso@unibg.it
[2]International Surveyance Compan, Antessano (Salerno) Italy - constantinoluismarino@hotmail.com
[3]Eng. Arch.Designer, PhD., Via L.Dalla Laita 16 -38061 Ala (Trento) - joel.a@hotmail.it

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ABSTRACT:
The degradation of Cultural Heritage sites is one of the biggest challenges in modern societies and it is becoming a pressing issue in many countries. Our Cultural Heritage is degrading faster today than any time in the past. Countries as Italy, boast a significant part of the heritage buildings and structures all over the world, typically made of stone. These countries are increasingly challenged to properly maintain their important legacy while keeping maintenance low-costs for the preservation. The degradation of historic masonry structures can be manifested in different ways that can be focused from different perspectives and disciplines. The present study-case deals with the Ponari Nymphaeum, a Roman building dated to the 1st century B.C., that has been the object of a study begun in 2010. The site is located on the slopes of Montecassino, in the Southern Lazio and it has been the object of a survey and monitoring begun in 2010, and updated to 2019, aimed at documenting the structural and architectural degradation of the site due to the negligence and the climate change by using the combined approach of the analytical and digital photogrammetry.The results show the efficiency of the proposed methodology to identify not only the existing state of degradation of the site, but also a useful approach to preserve and to reconstruct the missing and damaged parts that can be reproducted with high accuracy.

1. INTRODUCTION

Monuments preserved within historical and archaeological sites can be identified as test areas for analyzing the deterioration of the materials of the damaged manufacts through the application of innovative geomatic survey technologies such as photogrammetry. Priority can be given to those minor monuments that have not been thoroughly investigated to date, and for which accurate documentation is essential for the design of proper conservation, restoration and preservation interventions, as well as for the design of layouts and itineraries aimed at an aware fruition by the public. This is the case of the Ponari Nymphaeum on the slopes of Montecassino, that is located on the edge of the built-up area of Cassino in an area that is largely state-owned and managed by the Civic Archaeological Museum of Cassino, reporting to the Soprintendenza per i Beni Archeologici del Lazio. Partly owned by the University of Cassino and Southern Lazio, the Ponari Nymphaeum has been the object of a study begun in 2010, and continued over time until 2019, aimed at documenting the state of degradation and neglect over time by employing the analytical and digital frontiers of photogrammetry and by using high performance cameras.

2. STATE OF THE ART OF THE DEGRADATION OF CULTURAL HERITAGE

Architectural heritage is at risk for many reasons, including conflicts, climate change or even anthropic disasters; nevertheless, it is increasingly recognised as a driver of resilience which can more broadly support efforts to reduce disaster risks. Cultural heritage can make a direct contribution to sustainable development across economic, social and environmental dimensions in specific locations or contexts (Prieto et al., 2013; O'Brien et al., 2015; Rey et al., 2018;).
Climate change represents a prominent research topic over the last few decades, and climate impacts on Cultural Heritage, included historic and architectural manufacts have a special significance that has been recently recognised Major disasters present impactful consequences and have a large influence on heritage building performance, but they have a low probability of occurrence. Degradation effects related to climate change or rising sea levels occur over longer periods of time; nevertheless, when they occur, their effects are very serious in terms of the buildings′ performance (Tabaroff, 2000). In this sense, effective risk management of cultural assets is uncommon because of inadequate knowledge of the assets, failure to calculate the true cost of loss and damage, and the effects of external hazards. The maintenance of cultural assets is also closely related to place resilience (Pearson, 2008). In this sense, resilience is understood as the capacity to cope with, and recover from, aggressive external events, for example risks and effects of disasters such as earthquakes, conflicts and meteorological events driven by climate change, among so many others (Ortiz et al., 2014). Thus, the preventive conservation programmes analyse the risk of constructions; their main objectives are to improve knowledge of the current conservation conditions (vulnerability) (Ortiz et al., 2016) and threats (hazards) in order to minimize further degradation and to increase service life over time (Masciotta et al., 2020). Cultural heritage sites and monuments are usually subject (Fatorić et al., 2017) to i) static-structural hazards such as floods, geotechnical problems and seismic action; ii) environmental hazards such as weather conditions, pollution and current climate change effects; and iii) anthropogenic factors such as fires, vandalism as well as population and tourism effects. Concerning the intrinsic vulnerabilities of heritage constructions and the external hazards affections, the maintenance of the buildings must be considered like the process of keeping the construction in operation over time, preserving a balance between the performance of the building (functional service life) and the resources required for this to occur (Nigel, 2004). This implies that the management and maintenance of Cultural Heritage constructions consist of

identifying a series of relative priorities for intervention in terms of preventive maintenance actions (Neil Adger et al., 2005) note that *'adaptation that requires large-scale investment is likely to be episodic and staggered'*. Improvements to existing cultural heritage sites affected by climate-change-induced impacts might not be possible because of cost.

The degradation of historic masonry structures can be manifested in different ways as consequence of several environmental and anthropogenic factors that, when are cause of loss of materials, act on safety of critical elements and can severely compromise the structural integrity of the entire construction. Many studies, for example, deal with mathematical degradation models to predict the degree of deterioration of the materials, particularly of the calcareous stone. (Saba et al., 2018). Other studies focuse on experimental approaches using advanced structural health monitoring (SHM) techniques (Moropoulou et al., 2013), photogrammetry (Bitelli et al., 2017; Jalòn, 2020) , laser scanning (Bitelli et al., 2019) or radiometric methods (Lerma, 2011; Isuk et al., 2020; Hemmleb et al., 2006) to measure the degree of degradation of Cultural Heritage constructions so as to support decision making about preventive maintenance, restoration (Bozkurt et al., 2016; De Ferri et al., 2019; Núnez-Andrés et al., 2017), and resilience to climate change (Prieto et al., 2020).

The work could, eventually, be applied to other buildings and pathways of ancient Cassino including the theater, the so-called tomb of Ummidia Quadratilla, the stretch of paved road identified with Via Latina, the area of the Varronian Baths, and the presumed villa of Varro at Agnone. The whole area of the Varronian Baths represents a crosswalk corridor from the station to the Folcara through the extraordinary and unknown area of springs and streams of the aforementioned Baths, currently camping, to the rediscovery of the villa of the Roman erudite (later of Mark Antony) and his famous aviary, described by him and not yet surely identified (D'Urso et al., 2021; D'Urso et al., 2022). Recent occasional excavations make the location on the ground highly probable, and an area's arrangement could be followed by extensive excavation. Finally, in this context, the whole recovery of the unity of the urban center of Casinum, marginal to the modern city, could be linked to the route of the polygonal walls, still partially preserved, that connected it to its acropolis, in the place where the Abbey now stands. This could result in a highly evocative tour route in which the Christian monument and its classical antecedents could find full integration.

A long-term vision is required to develop appropriate strategies (Costamagna et al., 2020), including planning for disaster management and preservation strategies (Silva et al., 2016).

3. STUDY AREA AND DATA ACQUISITION

The Ponari Nymphaeum, named after the land's owners, is still preserved, in the former Roman area, at No. 13 on the road ss.149 to Montecassino. Although included, even recently, in some repertories on ancient nymphaea, the building is substantially still unrealized. The opportunity of a photogrammetric survey made it possible to identify new and interesting data, that contribute to a typological framework and the recognition of its degradation. The Ponari Nymphaeum represents a portion of a large urban dwelling dating back to the 1st century B.C. of which a rectangular room with rectangular niches is preserved, covered by a barrel vault, open to an atrium that was originally partially uncovered and equipped with a central marble basin.

The building is about half a meter below ground level. The cadastral parcel in which it falls (part. No. 578 of cadastral sheet No. 31 of the municipality of Cassino, prov. of Frosinone) is abandoned and periodically covered with thick brambles that make the area almost impassable. Even access to the environment, which is buried up to the lunette of the vault, is problematic. Inside, the terrain slopes down to the back wall, to a minimum of 1.30 meters above the original floor level. The room was partially excavated a few years before the last war, but it subsequently underwent progressive backfilling.

Figure 1. Cadastral 31 Cassino municipality part. 578

The nymphaeum room, currently a basement, has a rectangular floor plan (6.92x4.63x5.80 m) with the major axis orthogonal to the slope (51° North-West), and now, as in the past, is only open on the south-east side. Due to the backfilling, the wall heads are not visible and therefore the original length of the room cannot be determined, which, in any case, should not have exceeded 7 meters, if we assume a similar distance between head and niche as between the other niches and the 0.70-meter thickness of the walls.

The walls are enlivened by nine niches with a rectangular plan and flat roofing (0.65x065x1.40 meters): three on the short straight back wall and three distributed on each of the long sides, not perfectly symmetrical. A barrel vault with a depressed arch covers the room, set back 0.05 m on the side walls. The entire structure is made of cement of whitish mortar, not very fine but tenacious, and shapeless, compact white cement; more rarely, one notices in the cement mix sparse fragments of brownish travertine and isolated reddish brick fragments; in correspondence of the vault, a covering of shells and flakes,

even large ones, radially arranged.
The original mosaic flooring is preserved in both rooms, while part of the painted plaster with false marble incrustations and trompe-l'oeil perspective motifs, probably dating back to the 1st century A.D., remains on the walls, under which large sections of an earlier 'faux grotto' decoration with the insertion of shells, glass tesserae, and colored stones, typical of the central decades of the 1st century B.C., can be recognized.

Figure 2. Ponari Nymphaeum front elevation

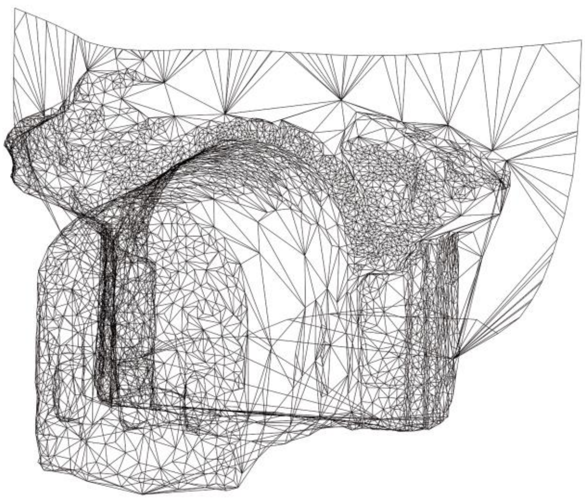


Figure 3. Ponari Nymphaeum 3D model

Figure 3 is a representation of the volume of the Ponari Nymphaeum from an external side perspective, in which the geometries of the vault and the front wall are evident. The effect of the rototranslation caused by the embankment thrust along the right perimeter wall, as well as the translation in the (x,z) plane of the entire structure, is already evident from the state of the entire wall structure dating back to the 2010 survey. The value of the height at the ridge of approx. 4.98 m and the width of approx. 6.66 m at the outer side walls were compared with later measured values in the 2019 survey.
In the first survey, dated back to 2010, photogrammetric measurements were made both by analogical and digital. Some measurements were analogically performed using film metric cameras, such as the Rollei Photometric 6008 camera equipped with calibrated and certified Carl Zeiss reseau and optics. Despite the evolution of technology, the obtained results were enormously accurate and comparable with those obtained with the use of more advanced processing software.

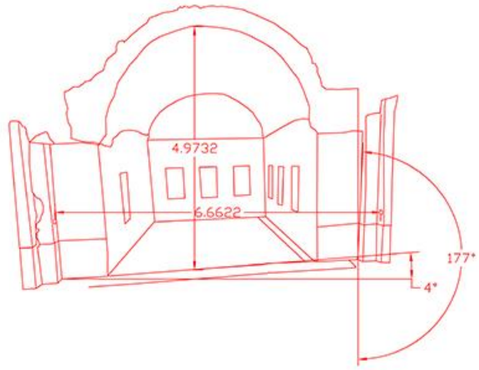


Figure 4. Wireframe pattern relative to the survey 2010

At the same time a digital camera, Sony ADSR 900, was used; at the time it was at the pinnacle of the highest-performing sensors and resolutions. It represented a link between analog and digital technology. However, while having comparable performance to traditional analog cameras, it had a sensor characterized by higher noise values and a lower dynamic range than traditional cameras.The optics used in photo shoots were produced by the same Carl Zeiss company. In recent years, the capabilities and corrections of aberrations in the optics, which are performed digitally since they are corrected through the use of software, have greatly increased. As far as the processing of images acquired with the Rollei Photometric 6008 camera is concerned, Rolleimetric CDW software was employed.
The location of the three station points are represented in Fig.5 and the coordinates of the targets with the values of the average residuals of the order of millimeters, of the three images, one central and other two lateral, are given in the table in Fig.6.

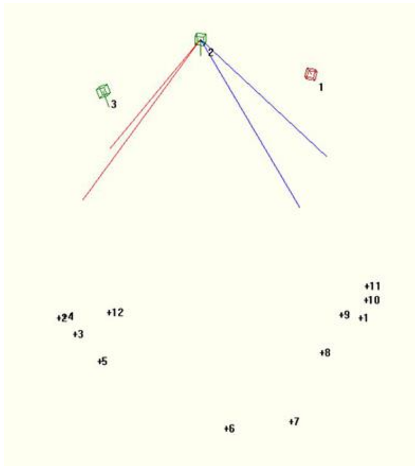
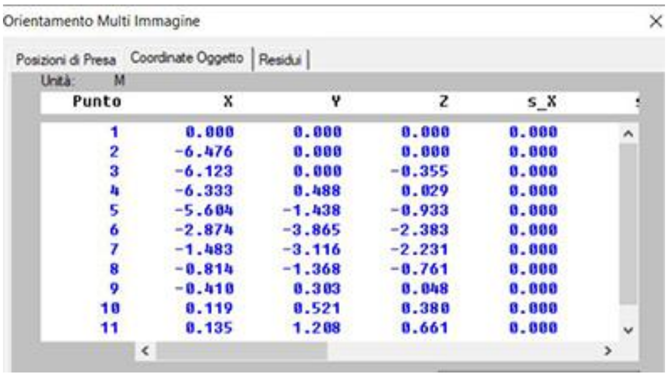


Figura 5. Station points with the Rollei camera

By exploiting the collinearity equations and by comparing the homologous points of the 3 images, the 3D coordinates of the targets highlighted in the "wireline" representation were calculated with millimeter accuracy.


Orientamento Multi Immagine

Posizioni di Presa | Coordinate Oggetto | Residui

Unità: M

Punto	X	Y	Z	s_X
1	0.000	0.000	0.000	0.000
2	-6.476	0.000	0.000	0.000
3	-6.123	0.000	-0.355	0.000
4	-6.333	0.488	0.029	0.000
5	-5.604	-1.438	-0.933	0.000
6	-2.874	-3.865	-2.383	0.000
7	-1.483	-3.116	-2.231	0.000
8	-0.814	-1.368	-0.761	0.000
9	-0.410	0.303	0.048	0.000
10	0.119	0.521	0.380	0.000
11	0.135	1.208	0.661	0.000

Figure 6. Targets’ coordinates

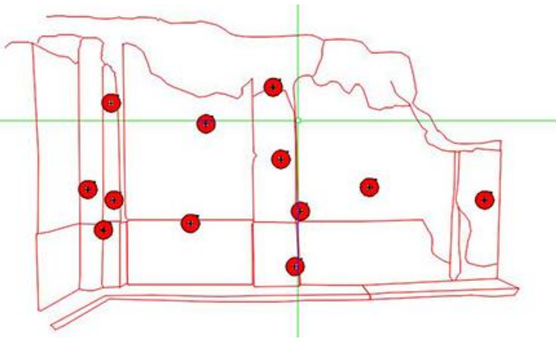


Figure 7. Wireframe pattern and targets of external wall West side

Figure 8. Central photogrammetric shoot

For a comparison three images, one central and two lateral, acquired with Sony ADSR 900 camera, in the 2010 survey, were processed with Agisoft Photoscan software version 8.3.1, with automatic production of a 3D model.
Therefore, from a semi-analogical survey approach we switched to a fully automated system with raster image generation, obtained by processing only three photo shoots, as shown in Fig.9, achieving a millimeter accuracy.
In 2019, a second survey was carried out employing a new camera, Sony A7R 4 with Carl Zeiss optics, and a back-illuminated sensor equipped with the highest possible resolution in mirrorless cameras (mirrorless cameras). From the digital processing of a set of 26 images, a raster image of the Nymphaeum was processed from which an orthoplan of the back wall with 3 compartments was extracted, of which three-dimensional measurements are available (Figs. 11-12). Thanks to the advantageous and useful presence of targets, affixed in the 2010 survey and still visible in 2019, it was possible to determine the changes in dimensions and displacements of the entire structure with millimeter accuracy.

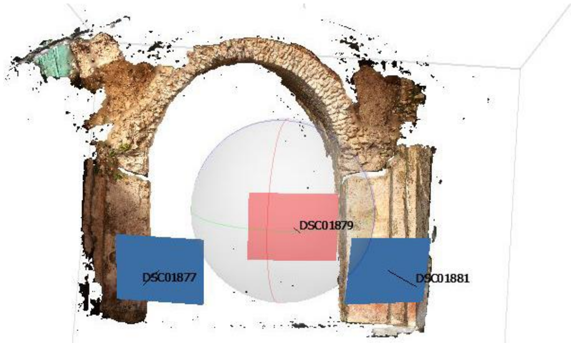


Figure 9. Digital processing images by ADSR900

Figure 10. Image elaborated by Agisoft Photoscan

Figure 11.Orthoplan of back wall

It was also possible to observe the variation of the floor level and the displacement (splaying) of the perimeter walls of the Nymphaeum, which compromise the stability of the vault of the structure and the containment of the lateral embankment.
The change in floor elevation shows an overall roto-translation movement of the entire structure, for which the inclination of the right pier of the arch was measured to be 3° from a perfect lead, and a rotation of 4° in its orthogonal direction (Figure 12).

The application of sophisticated machine-learning techniques simulates a digital darkroom and allows for an enormous improvement in image quality, achieving "super-resolution," through the use of purpose-created algorithms facilitating the reading of shadowed parts and those "burned" by strong illumination.

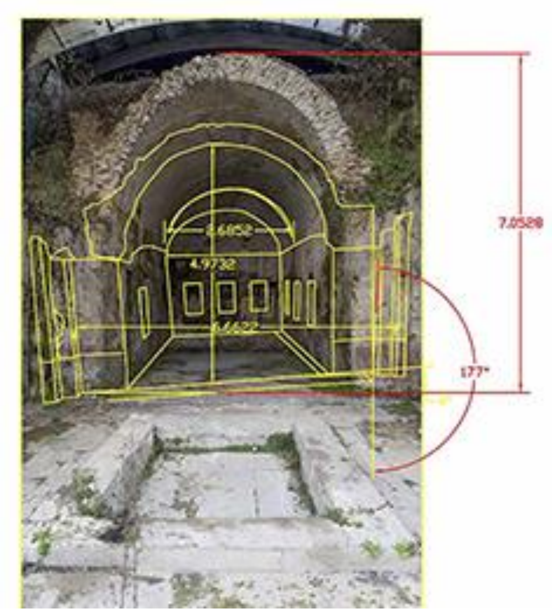


Figure 12. Roto-translation measurements

The roto-translation is the result of two photogrammtric acquisitions, the first, dated 2010, elaborated with the CDW software and the second, dated 2019, elaborted with the Photoscan software. The products of each elaboration are two wireframe drawings that are overlapped, so that highlighting the roto-translation.

4. DEGRADATION PROCESSING

The next phase of the work involved a different methodological approach since digital processing could not provide reliable results for determining both the variations in the colors of the frescoes and the areas, where obvious phenomena of degradation were manifested. Therefore, through the transformation of raw images to tiff images and, subsequently, to an orthoplan, it was possible to proceed to the determination of degradation surfaces and their increase in the last decade.
In addition to the measurement determination of surfaces, images could be obtained where the growth of mold and plants, plaster detachments, wall failures, and even structural damages in an extremely punctual and accurate manner was shown.
In this way, it was also possible to determine the variation in the coloration of wall frescoes, probably of plant origin, exposed to the weather and sunlight, and thus determine the geometry of the mosaic floors, their original shape and size.
The decay surface's widening is particularly evident in the outer left wall, as shown by the comparison of the two surfaces taken in the 2010 survey above on the 2019 survey, as depicted in Figure 13.

Figure 13. Visualization of degradation images, in the surveys 2010-2019, of the external side wall

As shown in the comparison of Figure 13, the measurements highlight a portion affected by high humidity at the right corner of about 0.71 sq. m. out of a total wall area of about 3.38 sq. m., and an area of about 0.57 sq. m. depicted at the left front, where there was an almost complete loss of the red color of the fresco due to the presence of white saltpeter powder consisting of potassium carbonate.

Figure 14. Comparison degradation surfaces in the surveys 2010-2019 of the external side wall

In this context, it is possible to determine, through the use of a color densitometer, the variation of density of the primary colors in the frescoes in the front of the outer side wall of the nymphaeum; so that their color hues can be used for conservative restoration. As it can be seen from the image in Figure 15, the representative values of the red color in the targets identified at two materialized points of the fresco surface, measured by a densitometer, are significantly different. In fact, in the 2010 survey, when the fresco was not totally deteriorated, the measured values of the RGB matrix of a target were Red:84, Green 29, and Blue 21, while, in the 2019 survey they changed, to the Red 200, Green 192, Blue 185 values of the RGB matrix, respectively, due to degradation.

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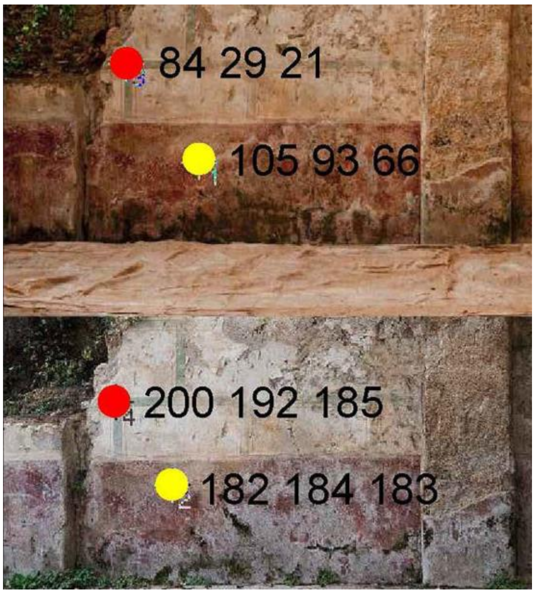

Figure 15. Variations of the color of the fresco in the surveys 2010-2019

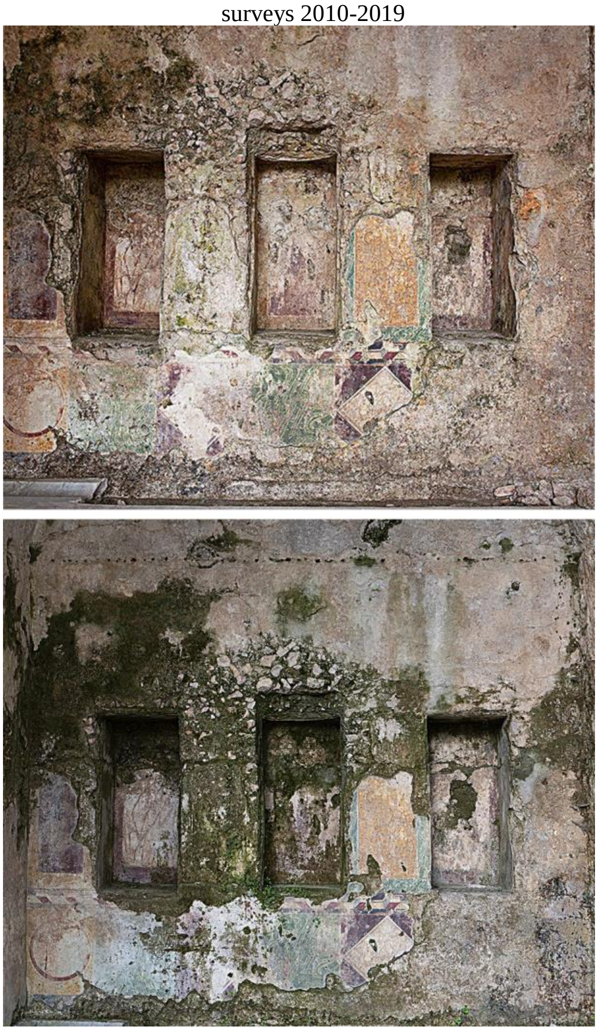

Figure 16. Comparison of degradation images, surveys 2010-2019 of the back wall

More degradation is evident in the background part depicted in Figure 16 related to the comparison of images from the 2010 and 2019 surveys obtained by matching homologous points. Water seepage from the embankment behind caused the formation of abundant vegetation and damage to the plasterwork and frescoes. The presence of moisture delimited in Figure 17 by the yellow-colored contours, respectively in the 2010 and 2019 surveys, affects areas covered by vegetation and mold; they increased from a value of about 1 square meter in 2010 to a much larger value of about 5.58 square meters in 2019.

Figure 17. Degradation increase measured in the survey 2019

The determination of these measurements was semi-analogically achieved. An analogical image acquired with a Rolleimetric with 121 reseau points was first transformed into a digital image by scanning and then transformed into an orthoplan on which the areas of degradation were measured manually using appropriate software. This approach was necessary because the photogrammetric cameras used in the survey dated 2010 were still mostly analogical. Conversely, the subsequent 2019 survey was entirely done digitally.
Similarly, an orthoplane can be generated in the pavement plane (x,z). For the reconstruction of the mosaic floor of the nymphaeum, a photogrammetric shoot was taken; subsequently the creation of an orthoplan allowed for the reconstruction by the symmetry of the entire floor.

Figure 18. Basic element of the mosaic floor

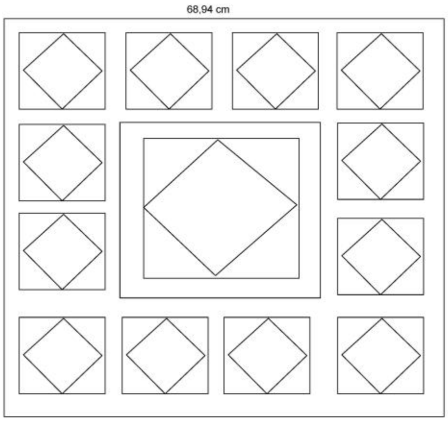

Figure 19. Extrapolated theoretical reconstruction by photogrammetric measurements

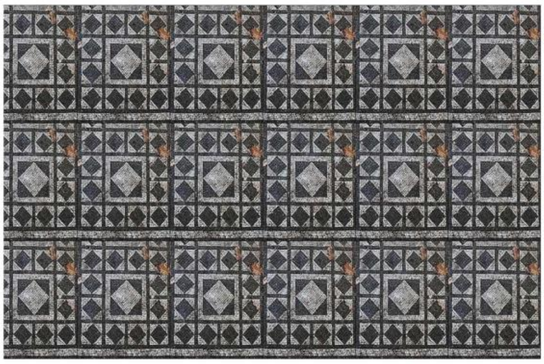

Figure 20. Virtual and theoretical reconstruction of the mosaic floor

Figure 21. Panoramic fusion of 3 shoots

The virtual reconstruction of a mosaic floor has been realized assuming that the geometric pattern of mosaic floor had this look. Furthermore, actually, by using CNC numerical control instrumentations, it is possible to reproduce the whole mosaic floor on the basis of the photogrammetric reconstruction of one tile.
A global assessment of the degradation conditions of the entire nymphaeum was obtained by a panoramic fusion operation of three single images (Fig.21) through the reading of the camera’s metadata (focal length, values and type of optical distortions), thus obtaining an image in which the evolution of the degradation is evident.
On the back wall of the nymphaeum the frescoes are less deteriorated due to less exposure to ultraviolet light. The color values of these frescoes should be considered as the basis for any restoration work on this site, as it is possible to numerically determine the composition of the original colors.

Figure 22. Orthoplan of the polychrome perimetral frames

5. CONCLUSIONS

The quantitative analysis carried out on the Ponari Nymphaeum through the photogrammetric technique and others allowed us to obtain both two- and three-dimensional measurements of very high precision, chromatic measures and information regarding the degradation of masonry and stone materials. Hence the proposed approach allows one to determine with millimetric accuracy, the dimensions of a damaged or deteriorated manufact or fresco.
Furthermore the percentage of the deteriorated parts can be measured, establishing an indispensable procedure in the execution of any reconstruction and/or restoration work, allowing for the commissioning and the designer the possibility of resorting to alternative techniques for the reproduction of architectural assets and manufacts through numerical control, machines that, by using photogrammetric measurements, produce negative copies subsequently colored.

REFERENCES

Alonso-Villar E.M.,Rivas T.,Pozo-Antonio J.S., 2019: Adhesives applied to granite cultural heritage: effectiveness, harmful effects and reversibility, *Construction and Building Materials*, 223, 951–964.

Bitelli G., Balletti, C., Brumana R., Barazzetti L., D’Urso M.G., Rinaudo F., Tucci G., 2017: Metric documentation of cultural heritage: research directions from the italian gamher project, in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W5. https://doi.org/10.5194/isprs-archives-XLII-2-W5-83-2017

Bitelli G., Balletti, C., Brumana R., Barazzetti L., D’Urso M.G., Rinaudo F., Tucci G., 2019: The Gamher research project for metric documentation of cultural Heritage: current developments, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W11. https://doi.org/10.5194/isprs-archives-XLII-2-W11-239-2019

Bozkurt T.S., Sayn B., Akcay C., Yildizlar B., Karacay N., 2016: Restoration of the historical masonry structures based on laboratory experiments, *J. Build. Eng.*, 7, 343 – 360.

Costamagna E.,Quintero M.S.,Bianchini N.,Mendes N., Lourenço P.B., Su S., Paik M., Min A.,2020:Advanced non-destructive techniques for the diagnosis of historic buildings. The Loka-Hteik-Pan tempe in Bagan,*J. Cult. Herit.*,43,108

D’Urso M.G., Manzari V., Marana B., 2021: A combination of terrestrial laser-scanning point clouds and the thrust network analysis approach for structural modelling of masonry vaults, *Acta Imeko*, 10-1, 257-264. IMEKO-ACTA-10 (2021)-01-34

D’Urso M.G., Valdambrini N., Marana B., Manzari V., 2022: Scans-to BIM for the Cultural Heritage: first results of a study case for a medieval church and its urban context, *Journal of Physics: Conference Series*, 2204, 012096. doi:10.1088/1742-6596/2204/1/012096.

De Ferri L., Santagati C., Catinoto M., Tesser E., di San Lio E.M., Pojana G., 2019: A multitechnique characteriztion study of building materials from the Exedra of S.Nicolò l’Arena in Catania (Italy), *J. Build. Eng.*, 23, 377 – 387.

Fatorić S., Seekamp E., 2017. Are cultural heritage ad resources threatened by climate change? A systematic literature review. *Climatic Change*, 142 (1-2), 227-254.

Formisano A., Marzo A., 2017:Simplified and refined methods for seismic vulnerability assessment and retrofitting of an italian cultural heritage masonry building, *Comput. Struct*.180,13 – 26.

Hemmleb M., Weritz F., Schiemenz A., Grote A., Maierhofer C., 2006: Multi-spectral Data Acquisition and Processing Techniques for Damage detection on Buildings Surfaces, *Image Engineering and Vision Metrology*, Dresden, Germany.

Isuk N., Halifeoglu F.M., Ipek S., 2020: Non-destructive testing techniques to evaluate the structural damage of historical city walls, *Construct. Build. Mater.*, 253, 119228.

Jalòn M.L., Chiachìo J., Gil-Martin L.M., Hermàndez-Montes E., 2020: Probabilistic identification of surface recession patterns in heritage buildings based on digital photogrammetry, *Journal of Building Engineering*, 34, 101922.

Lerma J.L., Cabrelles M., Portales C., 2011: Multitemporal thermal analysis to detect moisture on a building façade, *Construct. Build. Mater.*, 25 (5), 2190 – 2197.

Masciotta M.G., Roque J.C.A., Ramos L.F., Lourenço P.B.,2020: A multidisciplinary approach to assess the health state of heritage structures: the case study of the church of monastery of Jerónimos in Lisbon, *Construct. Build. Mater*, 253, 119228.

Moropoulou A., Labropoulos K.C., Delegon E.T., Karoglott M., Bakolas A., 2013: Non – destructive techniques as a tool for the protection of built cultural heritage, *Construct. Build. Mater.*, 48, 1222 – 1239.

Neil Adger W., Arnell N.W., Tompkins E.L., 2005: Successful adaptation to climate change across scales, *Glob. Environ. Chang.*, 15, 77 – 86, https://doi.org/10.1016/J.GLOENVCHA.2004.12.005.

Nigel D., 2004: Tensions and omissions in maintenance managment advice for historic buildings, *Struct. Surv.*, 22, 138 – 147, https://doi.org/10.1108/02630800410549035

Núnez-Andrés M.A., Buill F., Costa-Jover A., Puche J.M., 2017: Structural assessment of the roman wall and vaults of the cloister of Tarragona Cathedral, *J. Build. Eng.*, 13, 77 – 86.

O’Brien G., O’Keefe P., Jayawickrama J., Jigyasu R., 2015: Developing a model for building resilience to climate risks for cultural heritage, *J. Cult. Herit. Manag. Sustain. Dev. 5*, 99 – 114, https://doi.org/10.1108/JCHMSD-06-2013-0021.

Ortiz P., Antunez V., Martìn J.M., Ortiz R., Vázquez M.A., Galán E., 2014: Approach to environmental risk analysis for the main monuments in a historical city, *J. Cult. Herit.*, 15, 432 – 440, https://doi.org/10.1016/J.CULHER.2013.07.009.

Ortiz R., Ortiz P., 2016: Vulnerability index: a new approach for preventive conservation of monuments, *Int. J. Archit. Herit.*, 10, 1078 – 1100, https://doi.org/10.1080/15583058.1186758

Pearson M., 2008: Climate change and its impacts on Australia’s cultural heritage, *Hist, Environ.*, 21, 1, 37 – 40, https://australia.icomos.org/publications/historic-environment/he-vol-21-no-1-2008-global-climate-change-and-cultural-heritage/

Prieto A.J., Verichev K., Carpio M., 2020: Heritage, Resilience and Climate Change: A Fuzzy Logic Application in Timber-Framed Masonry Buildings in Valparaíso, Chile, *Building and Environment*, 106657.

Prieto-Taboada N., Ibarrondo I., Gómez-Laserna O., Martinez-Arkarazo I., Olazabal M.A., Madariaga J.M., 2013. Buildings as repositories of hazardous pollutants of anthropogenic origin, *J. Hazard Mater*, 242, 451-460.

Rey.R.,GonzálezP.V.,CarmonaJ.R.,2018:Structural refurbishment strategies on industrial heritage buildings in Madrid: recent examples, *Hormigón y Acero*,69 (285),e27– e35.

Riahi K., Rao S., Krey V., Cho C., Chirkov V., Fischer G., Kindermann G., Nakicenovic N., Rafaj P., 2011: RCP 8.5 – A scenario of comparatively high greenhouse gas emissions, *Clim. Change*, 109,33–57,https://doi.org/10.1007/s10584-011-0149-y.

Saba M., Quinones-Bolanos E.E., López A.L.B., 2018. A review of the mathematical models used for simulation of calcareous stone deterioration in historical buildings, *Atmos. Environ.*, 180, 156-166.

Silva H.F., Henriques F.M.A., 2015: Preventive conservation of historic buildings in temperate climates. The importance of a risk-based analysis on the decision makinf process, *Energy Build.*, 107, 26 – 36.

Tabaroff J., 2000: Cultural heritage and natural disaster: incentives for risk managment and mitigation, in A. Kreimer, A. Margaret (Eds.), *Manag. Disaster Risk Emerg. Econ.*, 71 – 79, New York: The World Bank.