RESTORATION WORKFLOWS BY MEANS OF PHOTOGRAMMETRY: THE CASE STUDY OF PASHAS BRIDGE

I. Tavantzis[1], Z. E. Tsifodimou[1], I. Skalidi[1], E. Karachaliou[1], I. Giannaris[1], A. Bakousi[1], A. Skondras[1], K. Katakalos[2], E. Stylianidis[1]

[1] School of Spatial Planning and Development, Faculty of Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece - (tvioannis, zoieirini, iskalidi, ekaracha, skondrasa, sstyl)@plandevel.auth.gr, kbakousi3@gmail.com
[2] School of Civil Engineering, Faculty of Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece - email kkatakal@civil.auth.gr

KEY WORDS: Cultural Heritage; 3D Modelling; UAV; Photogrammetry; Laser Scanning; Monument Restoration.

ABSTRACT:

The restoration of cultural heritage sites is a complex and challenging process, particularly when the structure holds significant historical and cultural value. This paper refers to the first stages of the restoration study of Pashas Bridge, one of the largest stone bridges in Greece that was destroyed during World War II and further damaged by an earthquake in 1995. The project was assigned to multiple research groups from the Aristotle University of Thessaloniki (AUTh) for a period of 18 months by the Greek Ministry of Culture and Sports. To restore the bridge effectively, it is essential to accurately record, document, and assess its current condition. Through the use of photogrammetry, which creates 3D models of objects or structures using images, and unmanned aerial vehicles (UAVs) which assisted in capturing multiple shots with various angles of the bridge, a detailed 3D model of the bridge's current condition was generated. In addition to these technical approaches, historical research and documentation were utilized to understand the bridge's cultural heritage value. The process included an examination of historical photographs and records related to the bridge, with a constant effort to discover additional information about its history and importance. Ultimately, the restoration process of Pashas Bridge serves as a valuable case study for the effective restoration of cultural heritage sites. Through utilizing these resources, the team aims to restore the bridge to its former glory, preserving its cultural heritage value and ensuring its place as a valuable and integral part of the community for generations to come.

1. INTRODUCTION

1.1 Historical Overview

Stone bridges constitute a notable portion of Greece's built historical heritage; over 700 stone bridges have been recorded (Beligiani, 2007), with the majority of them still functioning. In pre-industrial Greece, stone was the main construction material, and safe passage over waterways was a significant challenge. Unskilled craftsmen could only build stone bridges, either single-arched or multi-bowed, as a practical solution to this transportation issue until the 20th century (Grassos, 2007).

Stone arched bridges are usually built in hard-to-reach areas which, when coupled with the high degree of urbanization in many parts of the Greek countryside, makes them difficult for the local population to access. As a result, people's knowledge and awareness of these bridges are often limited and in numerous instances, they are not even cognizant of their existence. Consequently, a considerable number of these bridges have deteriorated and have been adversely affected by the passage of time.

The complete integration of the bridges into their natural surroundings has inspired their scholar, Manda, to state that humans, in order to fulfil their need for communication, were forced to extend nature itself by building these masterpieces of folk architecture in total harmony with their surrounding natural environment (Mandas, 1984). These masterpieces are regularly used as topoi for urban myths and traditional folklore tales and the case of Pasha's bridge does not constitute an exemption.

Believed to be built around 1690 by Mahmud Pasha, this bridge is considered the biggest and oldest stone bridge that ever existed in the prefecture of Western Macedonia (Figure 1, Figure 2). It is situated between the villages of Siatista and Paleokastro, close to Grevena. The name of the bridge is mentioned in the travel journals of F. Pouqueville as he states that (he) "traversed a stone bridge with 5 uneven arches. A long Turkish sign states that a Roumili Valesi built it to thank God for one of his wives fell in the river and was saved by a miracle" (Pouqueville, 1985). Underneath its biggest arch, a bell was placed to caution travellers against crossing. It spanned a distance of over 100 meters, with the primary arch measuring over 15 meters in height. To impede the German invasion to the south, British and New Zealander soldiers detonated it on April 14th, 1941.

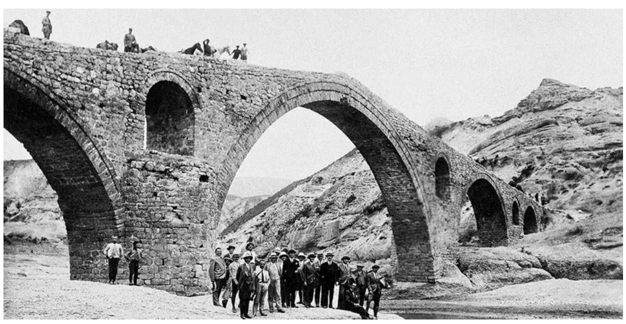

Figure 1. Old photo of the bridge as published in the photographic album of Vangelis Nikolopoulos "Greece, Grevena 1912-1940, Photographic Documents and Records", 2018
(source: https://grevena.pdm.gov.gr/ta-scholeia-xanachtizoyn-to-gefyri-toy-pasa-stin-kokkinia-grevenon/)

Figure 2. Turkish cavalry at Pasha's Bridge in 1905
(source: https://www.sansimera.gr/articles/1430)

The remnants have also been heavily impacted by the 6.6 magnitude earthquake that hit the nearby town of Kozani in 1995 (Papanastassiou et al., 1998) and have remained in a state of deterioration ever since (Figure 3).

Figure 3. Bridge's current remains.
(source: Photos from field survey)

1.2 Motivation

The preservation of our built cultural heritage holds a significant role in shaping our understanding of the past, identity, and economic and social well-being. They are tangible remnants of past civilizations, and they offer unique insight into our history, values, and aesthetics of bygone eras. Moreover, they shape our collective sense of identity and sense of place, acting as cultural anchors, fostering social cohesion, and supporting community ties. The precise documentation, cross-disciplinary analysis, upkeep, and preservation, and finally the promotion of stone arched bridges serve to showcase these structures as distinctive exemplars of our nation's cultural heritage.

The Ministry of Culture and Sports awarded AUTh the entire 18-month restoration study of the Pasha's bridge. This paper examines the initial phase of the restoration project of the Pasha historical bridge, which involved the documentation and recording of the monument's current condition. It outlines the approach, findings and methodology that will serve as the basis for the restoration and reconstruction of the bridge. The culminating goal is to contribute to the conservation of our cultural legacy and the development of effective techniques for restoring monumental structures.

1.3 Related Literature

Producing a precise three-dimensional (3D) model of a cultural heritage artifact or site necessitates a considerable amount of technical expertise and customized methodologies that are tailor-made to the specific requirements of the artifact or site, including its present state, location, accessibility, and surrounding environment. There are numerous commonly used methodologies for acquiring the data needed to create accurate 3D models, which typically involve a combination of techniques such as photogrammetry, laser scanning, structured light scanning, computed tomography (CT) scanning, and sonar imaging. In the work of Barsanti (Gonizzi Barsanti et al., 2014), the appropriate workflow and best practices when dealing with 3D digitization projects are analysed.

When encountering inaccessible and challenging environments, utilizing UAVs for data acquisition is considered one of the most effective approaches; they possess the ability to capture high-quality imagery and data from unique vantage points and inaccessible areas in high-risk sites. A comprehensive overview of the status of UAVs in geomatics applications, along with novel opportunities, is thoroughly discussed in Nex's review (Nex & Remondino, 2014) and in Remondino's research (Remondino, 2011). The investigation conducted by Pan's team (Pan et al., 2019) provides an insightful exploration of automated techniques using UAV-based photogrammetric point clouds for producing surface models of the structural components of heritage bridges. In Murtiyoso's review (Murtiyoso & Grussenmeyer, 2017), the fundamental principles and techniques involved in image-based documentation of heritage structures using photogrammetry and Structure from Motion (SfM) methodologies are explored, along with an evaluation of software tools for point cloud generation. The combination of UAV photogrammetry with 3D modelling techniques to capture and represent complex architectural structures such as bridges has been explored in numerous notable scholarly case studies: (Mongelli et al., 2017), (Pepe & Costantino, 2021), (Kouimtzoglou et al., 2017) and (Denker, 2022).

By introducing Artificial Intelligence (AI) techniques into UAV-acquired data for bridge 3D modelling, the accuracy and efficiency of the modelling process can be improved. AI can assist in the automatic recognition of the structural components and textures of the subject, as well as in the generation of 3D point clouds and surface models. It can reduce human error, especially when dealing with large datasets or complex structures ((Rakeh Saleem et al., 2020), (Sabato et al., 2023), (Zhang & Yuen, 2022)).

Nevertheless, the usage of AI in heritage preservation and restoration is still limited due to the lack of available training and validation datasets and the lack of ground truth data. Furthermore, it can be computationally expensive and require high processing power and specialized hardware. The importance of expert knowledge and experience in the preservation and restoration process is often neglected, indicating that AI shouldn't be considered as a substitute but rather as a supplementary tool of the process.

2. METHODOLOGY

2.1 Workflow

The SfM approach is increasingly popular in cultural heritage documentation due to its ability to create high-resolution 3D models from 2D images. The typical SfM workflow commonly consists of four main steps: image acquisition, image pre-processing, feature extraction/matching and 3D reconstruction. The generated 3D model is an excellent steppingstone for conducting structural and functional analysis which can highlight the material properties, stability, and load-bearing capacity of the structure in question. The 3D model allows for greater accuracy and precision in these assessments, leading to more informed decision-making in historical restoration projects.

The pipeline which outlines the primary steps of the team’s restoration project is depicted in Figure 4.

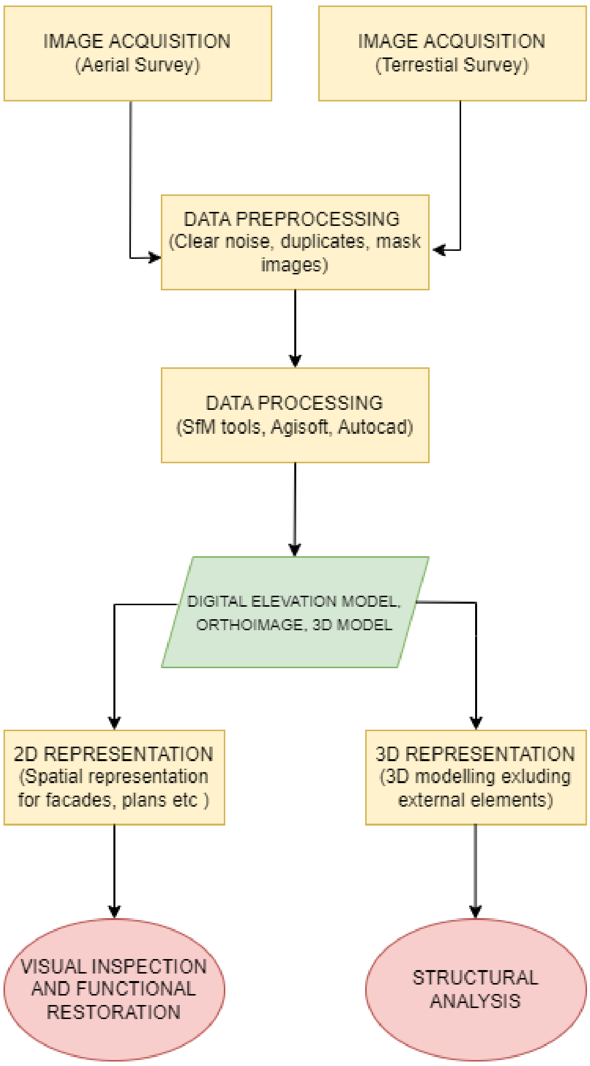

Figure 4. Workflow of the SfM approach and further possible structure and functional analysis

2.2 Data Collection

The field data was collected through the combination of terrestrial and aerial techniques. Terrestrial measurements were obtained using GNSS equipment, specifically the GGRS87/Greek Grid, with seven ground control points (GCPs) strategically placed across the study area. A Phantom UAV was used for the aerial data collection, with a total of 1350 camera shots captured in the WGS84/EPSG:4326 coordinate system. The study area (Figure 5,Figure 6) encompassed 1,654 km2, and the distribution of GCPs was taken into account.

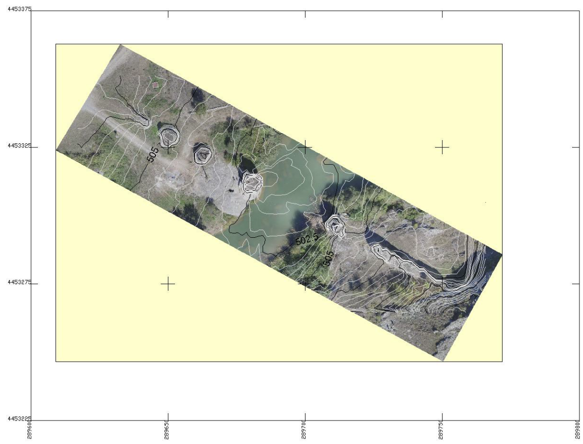

Figure 5. Orthophoto in GRS87 Greek grid, Scale 1:500 (source: AutoCAD 2023)

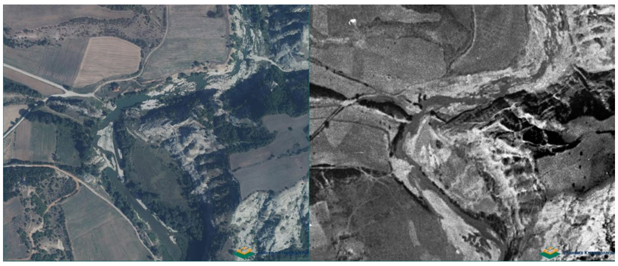

Figure 6. Aerial Photo 2015-2016, 1945-1960 Scale 1: 2500 of the respective area of interest (source: Hellenic Cadastre, https://maps.gov.gr/gis/map/)

2.3 Data Processing

The collected data was processed using the Agisoft Metashape Pro (Agisoft, 2021). Out of the 1350 captured images, a total of 1160 images were finally imported and used for alignment. The point cloud generated contained 37,993,185 data points, including noise and water data. GCPs from a txt file were inserted, with control points having an accuracy of **6 cm** both horizontally and vertically (Table 1). This level of accuracy is considered good, and it ensures that the resulting 3D model is reliable and can be used for accurate measurements and further analysis.

Table 1. Control points RMSE (in cm)

X error	Y error	Z error	XY error	Total
4.82483	2.29183	3.6095	5.34148	6.4467

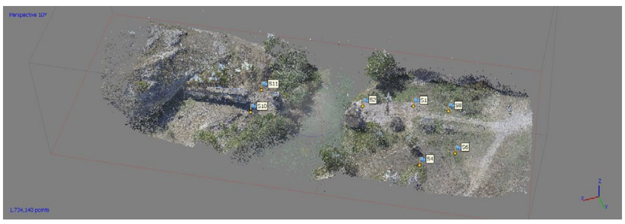

Figure 7. Point Cloud (source: Agisoft Metashape Pro)

The final step in the data processing was the creation of a Digital Elevation Model (DEM) (Figure 8). DEMs provide detailed and accurate information on the topography and the terrain of the site in question. The slope, elevation and drainage patterns can facilitate the designing of the restoration plans especially when they are sensitive to the site’s original features.

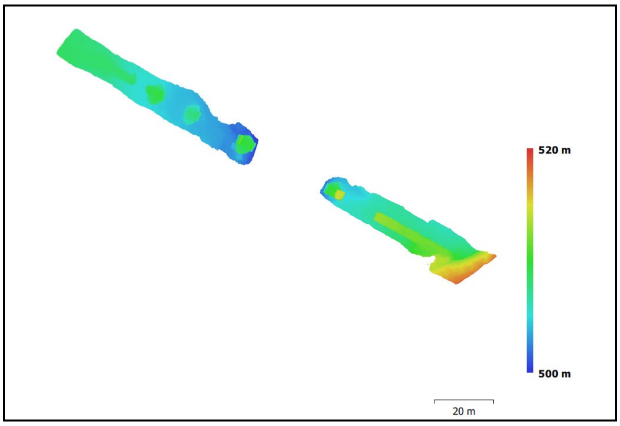

Figure 8. DEM of the respective area with a resolution of 20m (source: Agisoft Metashape Pro Report)

The aggregated DEM with a resolution of 20 meters, covered an elevation range of 498m to 526m on the Z-axis. Quality indices for the DEM included a resolution of 3.51 cm/pixel and a point density of 812 points/m. Overall, the integration of both terrestrial and aerial techniques provided comprehensive results of the study area.

The final produced 2D model was imported in AutoCAD and measurements from both sides were incorporated where measurements from both sides were incorporated to enhance precision and comprehensibility (illustrated in Figure 9 and Figure 10).

The resulting visualization serves as a useful reference for any future restoration efforts, ensuring that any new additions or enhancements to the bridge are both accurate and complementary to the actual size of the building.

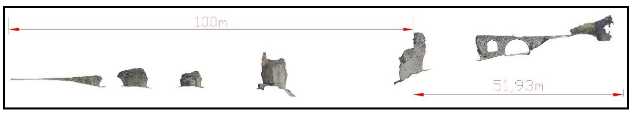

Figure 9. View 1 of the bridge current condition (remains of the bridge)
(source: AutoCAD 2023)

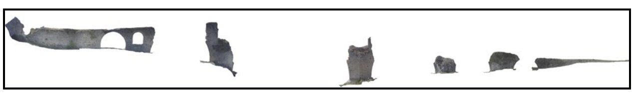

Figure 10. View 2 of the bridge current condition (remain of the bridge)
(source: AutoCAD 2023)

2.4 3D Model

The resulting 3D model of the remains (Figure 11, Figure 12) demonstrates a shadowless object, indicating that our photographs used to create it were taken from good angles and encompassed the entirety of the needed area. The depiction is accurate and dense, a fact which can be validated by the detailed stone texture of the remains visible in the model.

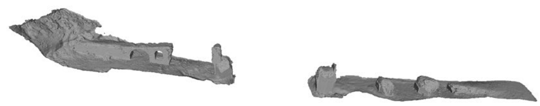

Figure 11. Bridge's 3D model
(source: MeshLab (CNR, 2023))

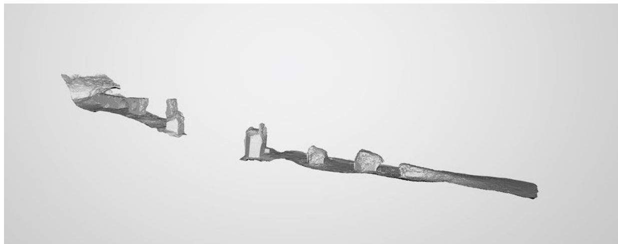

Figure 12. Bridge's texture model
(source: MeshLab (CNR, 2023))

3. CONCLUSION

3.1 3D Model from Historical Data

Producing an accurate 3D model from historical images proved to be a difficult task for our team. The production of a 3D model from historical images poses a significant challenge, primarily due to the direct correlation between the quantity and quality of the images and the resulting model's accuracy. In cases where the historical images are limited in quantity or in poor quality, the software may not be able to generate a 3D model.

That was the case for the bridge of Pasha, as the availability of pictures was limited and in poor quality due to the scarcity of photography in the area at the time of its destruction in 1941. Additionally, all the sourced images depicted only one side of the bridge, hindering the production of an accurate 3D model. Despite our efforts to enhance the dataset with an addition of current photographs of the bridge, they did not yield any significant improvements in our attempts to produce a 3D model from historical data.

3.2 Future Steps

The ulterior motive behind the production of the accurate 3D model of the remains of the bridge is to provide valuable and detailed information regarding the structure’s geometry to the restoration team. If the 3D model depicts the spatial relationship of the structure accurately, volume estimation, material estimation, cost analysis as well as planning and execution of detailed interventions can be obtained from it. Moreover, detailed interventions such as an addition of new element or the removal of existing ones can be planned with more ease since the precise measurements and analysis of the structure is at hand. This demonstrates the important contribution of 3D modelling in building restoration and conservation. Its existence safeguards the efficient and effective nature of any restoration project and maximizes its longevity.

https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1543-2023

Since our efforts could not produce an accurate 3D model from the historical pictures of the bridge which would exhibit its original shape and beauty, we are now faced with the challenging task of extracting precise points from the old historical photographs of the arched bridge by image matching. The actual original geometry of the bridge can be precisely reconstructed by juxtaposing the measured points on the actual remains of the bridge with their corresponding points on the historical photos. This will allow us to measure the original arches' height, span, and thickness, which are critical dimensions and hold a crucial part in the restored bridge's structural and artistic integrity.

The aim of the restoration team is to revive the bridge to its former glory while retaining its unique character and acknowledging the passage of time that has left its mark on the structure. This delicate process requires restorers to use their expertise to re-establish the bridge's original appearance as much as possible, making it blend seamlessly into its surroundings. This approach is crucial, especially in the case of a functional structure such as a bridge, where its restoration must not only capture the essence of the original, but also ensure its longevity and functional stability for future generations.

REFERENCES

Agisoft. (2021). Agisoft Metashape, 2.0.1. Retrieved April 1, 2023, from https://www.agisoft.com/

Beligiani, E. (2007). Searching for the stone bridges of Greece. Athens: Livani Publishing.

Denker, A. (2022). Palmyra in Context: An Intelligent Reality Application to Revive the Victimized "Bride of the Desert". EEE 2nd International Conference on Intelligent Reality (ICIR) (pp. 35-38). Piscataway, NJ: IEEE. doi:10.1109/ICIR55739.2022.00023

Gonizzi Barsanti, S., Remondino, F., Fernández-Palacios, B. J., & Visintini, D. (2014). Critical Factors and Guidelines for 3D Surveying and Modelling in Cultural Heritage. International Journal of Heritage in the Digital Era, 141–158. doi:10.1260/2047-4970.3.1.141

Grassos, G. (2007, December). The stone arched bridges of Greece. Retrieved from EDULL Repository: http://repository.edulll.gr/edulll/handle/10795/1228

ISTI-CNR. (n.d.). MeshLab, 2022. Retrieved April 1, 2023, from https://www.meshlab.net/

Kouimtzoglou, T., Stathopoulou, E. K., Agrafiotis, P., & Georgopoulos, A. (2017). IMAGE-BASED 3D RECONSTRUCTION DATA AS AN ANALYSIS AND DOCUMENTATION TOOL FOR ARCHITECTS: THE CASE OF PLAKA BRIDGE IN GREECE. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 391–397. doi:10.5194/isprs-archives-XLII-2-W3-391-2017

Mandas, S. (1984). The Epirus Bridges. Athens: TECHNICAL PRESS SA.

Mongelli, M., De Canio, G., Roselli, I., Malena, M., Nacuzi, A., & de Felice, G. (2017). 3D Photogrammetric Reconstruction by Drone Scanning for FE Analysis and Crack Pattern Mapping of the “Bridge of the Towers”, Spoleto. Key Engineering Materials, 423-430. doi:10.4028/www.scientific.net/KEM.747.423

Murtiyoso, A., & Grussenmeyer, P. (2017). Documentation of heritage buildings using close-range UAV images: dense matching issues, comparison and case studies. The Photogrammetric Record, 206-229. doi:10.1111/phor.12197

Nex, F., & Remondino, F. (2014). UAV for 3D mapping applications: a review. Applied Geomatics, 1–15. doi:10.1007/s12518-013-0120-x

Pan, Y., Dong, Y., Wang, D., Chen, A., & Ye, Z. (2019). Three-Dimensional Reconstruction of Structural Surface Model of Heritage Bridges Using UAV-Based Photogrammetric Point Clouds. 1204. doi:10.3390/rs11101204

Papanastassiou, D., Drakatos, G., Voulgaris, N., & Stavrakakis, G. (1998). The May 13, 1995, Kozani-Grevena (NW Greece) earthquake: Source study and its tectonic implications. Journal of Geodynamics, 233-244. doi:10.1016/S0264-3707(97)00068-9

Pepe, M., & Costantino, D. (2021). UAV Photogrammetry and 3D Modelling of Complex Architecture for Maintenance Purposes: the Case Study of the Masonry Bridge on the Sele River, Italy. Periodica Polytechnica Civil Engineering, 191–203. doi:10.3311/PPci.16398

Pouqueville, F. (1985). Journey to Western Macedonia (Spring of 1806). Thessaloniki: Kiriakidis Bros Publishing.

Rakeh Saleem, M., Park, J.-W., Lee, J., Jung, H.-J., & Zohaib Sarwar, M. (2020). Instant bridge visual inspection using an unmanned aerial vehicle by image capturing and geo-tagging system and deep convolutional neural network. Structural Health Monitoring, 1–18. doi:10.1177/1475921720932384

Remondino, F. (2011). Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning. Remote Sensing in Natural and Cultural Heritage, 1104-1138. doi:10.3390/rs3061104

Sabato, A., Dabetwar, S., Kulkarni, N., & Fortino, G. (2023). Noncontact Sensing Techniques for AI-Aided Structural Health Monitoring: A Systematic Review. IEEE Sensors Journal, 4672 - 4684. doi:10.1109/JSEN.2023.3240092

Zhang, Y., & Yuen, K.-V. (2022). Review of artificial intelligence-based bridge damage detection. Advances in Mechanical Engineering. doi:10.1177/168781322211227

APPENDIX

Figure 13. Ground Control Points on site

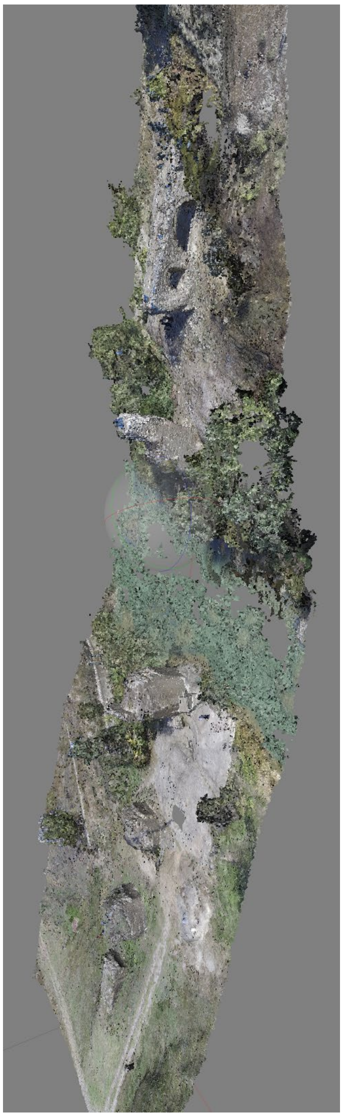

Figure 14. Dense cloud before the removal of vegetation and surrounding environment