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Detection and documentation of stone material deterioration in historical masonry structures using UAV photogrammetry: A case study of Mersin Aba Mausoleum

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Abstract

The Aba mausoleum, located in the ancient city of Mersin Kanlıdivane, is one of the most well-known places in the region. Although the architectural integrity of the building is partially preserved, material deterioration and structural deformations are observed especially on the west and north walls. Since the monument is one of the few examples of architectural and structural integrity that still exists, it should be included in the architectural preservation program as soon as possible before it loses its structural integrity. Accurate identification of the causes and types of degradation is of great importance in designing conservation interventions. In this study, it is aimed to detect and document the stone material deterioration of Mersin Aba mausoleum, which is a great necessity for the sustainability of cultural heritage, by using UAV photogrammetry. UAV photogrammetry and mapping techniques were used as a method in the study. The data obtained as a result of the study show that, thanks to their high resolution, a deterioration map can be created for the detection of material deterioration and restoration analysis quickly and easily. In addition, as a result of the study, it is seen that the most common types of stone material deterioration in the building are surface pollution, cracks and exfoliation. According to this result, it is seen that even the types of material problems based on the smallest detail can be determined based on virtual visual inspection, thanks to UAV photogrammetry, without observing the structure on-site with UAVs.

1. Introduction

A large percentage of the world's tangible cultural heritage is made of stone, and stone monuments are slowly but irreversibly disappearing. For example, it has been calculated that limestone will erode an average of 1.5-3 mm of rock within 100 years in temperate climates and will cause the loss of inscriptions on tombstones in the United Kingdom within 300 years [1]. When the causes of material deterioration in historical stone structures are examined, it is seen that the most common cause of material deterioration in stone structures in the world is caused by natural environmental factors or human-induced reasons. For example, rain water, which is a natural environmental factor, penetrates into the stone and accelerates the freezing/thawing cycles and dissolution processes of the stone. In addition, pollutants in the air can be carried into the stone by rain water and can play an important role in the deterioration of the stone, as it accelerates the formation of a black crust called surface pollution by chemical decomposition of the stone [2]. Rands et al. [3] found that both acidity and ionic strength in rainwater play an important role in limestone degradation. Butlin et al. [4] show that sulfur dioxide makes a significant contribution to the degradation of calcareous stones in high pollution areas and is a major cause of stone dissolution, particularly in the United Kingdom. The types of material degradation caused by these causes are seen in many different types, including cracking, blistering, surface loss, fragmentation, discoloration, biodegradation and damage from previous intervention [5-16].

Different new technologies have been developed in surveying of architectural documentation. Digital photogrammetry, 3D Laser Scanning and UAV are some of the surveying Technologies of cultural heritages. The development of digital photogrammetry to use cultural heritage is provided simplicity on the works carried out either on the field or on the laboratory. As a result of this development, the application of the photogrammetry science on the various topics is increased its application to be used much more effectively [17-20].

The use of three-dimensional computer graphics and visualization techniques is becoming more and more popular, because these techniques visualize more realistic object models than graphic based object models [21-27].

The other modern technology of measurement of cultural heritages is laser 3D laser scanning. Laser Scanning is a non-contact, technology that digitally captures the shape of physical objects using laser light. 3D laser scanners create "point clouds" of data from the surface of an object [28-33].

Using of unmanned aerial vehicles (UAVs) are becoming more effective tools for researchers for their applications. unmanned aerial vehicle is a very beneficial tool to obtain information without touching the object. [34-38].

For the treatment of material deterioration seen on the facades of historical buildings, first of all, the types of deterioration must be correctly identified. In some cases, it is possible to solve the deterioration of stone structures without touching the structures, only by improving the environmental conditions. In this context, it is very important to correctly diagnose the cause of deterioration in stone material [39]. Mapping the deterioration of facades in urban historical contexts represents a preliminary activity for the preparation of any restoration project [2]. However, the creation of deterioration maps of facades by manual methods is time consuming and laborious.

In the literature, it is seen that terrestrial laser scanning, photogrammetry and also unmanned aerial vehicles called "drones" are used in the creation of material deterioration maps of facades. The use of digital tools to support mapping activities has resulted in more detailed results on facade analysis, leading to simplification of its operations [40]. Surveys based on terrestrial laser scanning (TLS) tools in the literature yield very good geometric data in terms of high resolution, high accuracy and low uncertainty, but often yield dense point clouds that are not useful for disturbance mapping. Because color data is not always reliable in TLS data, this shortcoming is partially compensated by adding an external high-performance digital camera or collecting large numbers of photos to create high resolution (HDR) images [41]. In addition, the data obtained from TLS is limited to the camera angle [42] and it is considered to be relatively difficult to access due to the expensiveness of the instruments used [43]. In addition, site conditions and obstructions caused by different types of objects (for example, structural components that cause self-shadowing) in historical buildings may make the application of this technique insufficient for general research. It is seen that terrestrial laser scanning or terrestrial photogrammetry applications do not give satisfactory results in this case, since the deterioration mapping of facades is difficult in historical urban contexts, which are often characterized by narrow streets and tall buildings. In the researches, it is emphasized that the use of UAV photogrammetry in the deformation maps of the facades has several advantages over terrestrial laser scanning and photogrammetry methods. The common emphasis in these studies is that the use of UAVs equipped with commercial cameras leads to lower vehicle cost, higher data collection speed, and most importantly, better representation of materials and material issues [44-46]. In addition, the use of UAV photogrammetry is low cost, fast and easy to use compared to terrestrial laser scanning [2]. In the studies, it is stated that the UAV photogrammetry method is also the best solution to overcome the terrain limitations and to investigate the facade areas that are hidden from the ground or inaccessible [47].

In many studies, it has been found that it is easily possible to model buildings from close range or to monitor material deterioration using UAVs [48-51]. Russo et al. [2] used UAV photogrammetry to analyze the facade of a large historic building in Bologna (Italy), and as a result of the study, geometric data as well as material information useful for architectural analysis and restoration planning were obtained. The results of the study show that with the drone it is possible to obtain a metric orthophoto image of the facade of a historic building of suitable quality for a detailed mapping of stone material degradation. In addition, the obtained data showed that, thanks to their high resolution, a deterioration map can be generated quickly and easily to support restoration analysis. Cavalagli et al. [51] conducted photogrammetric research with drones to create a 3D model and damage maps of a historic stone arch bridge located in the ancient Via Amerina (Todi, Perugia, Italy). As a result of the study, it was determined that the assessment of structural damage by photogrammetric research with UAVs and especially cracks, microcracks and material shortages can be mapped without direct access and this can be done based on virtual visual inspection. In addition, in the study, the point cloud obtained by UAV photogrammetric research was compared with a point cloud based on the TLS survey, as a result, it was shown that the UAV-based research method provides more material resolution than the TLS method and can provide significant advantages by reducing the working time. In the application to a severely damaged historical structure, the study showed that the use of UAV-based photogrammetry can provide a detailed detection of all types of material deterioration, including surface loss and significant cracks in the structure, and is very effective in quickly highlighting damage and estimating missing material volumes. Such a methodology has proven to be very effective for the investigation of inaccessible structures and for the quantitative estimation of damage to historic masonry structures.

Although the architectural integrity of the Aba mausoleum in Mersin Kanlıdivane Ancient City is partially preserved, material deteriorations and structural deformations are observed especially on the west and north walls. Accurate identification of the causes and types of degradation is of great importance in designing conservation interventions. In this study, it is aimed to detect and document the stone material deterioration of Mersin Aba mausoleum, which is a great necessity for the sustainability of cultural heritage, by using UAV photogrammetry.

2. Study Area

The Aba Mausoleum, an ancient monument built in the 2nd century AD in the Kanlıdivane Region of Mersin province of Turkey, has coordinates 36°31'38.5"north, 34°10'37.4" east (Figure 1). This structure, built in the type of Roman temples, is the most magnificent mausoleum in the ancient city. According to the inscription on the door of the mausoleum, it was built by a woman named Aba for herself and her husband Arios. Based on the inscription and other tombs on it, the tomb is dated to the 2nd century AD. The Aba Mausoleum is located to the north of the geological pit in the region and is one of the best-known places in Kanlıdivane.

The tomb monument is built on a low podium, has a vaulted entrance on the front and has Corinthian plaster capitals on its four corners. The building was built with the masonry technique and was built of cut stone. Mortar was used as the binding material. The roof of the superstructure is in the form of a cradle and is stone paved. The last row of cut stones on the masonry walls was built in the architrave style, and the cornerstones were made in the Corinthian capital style [52].

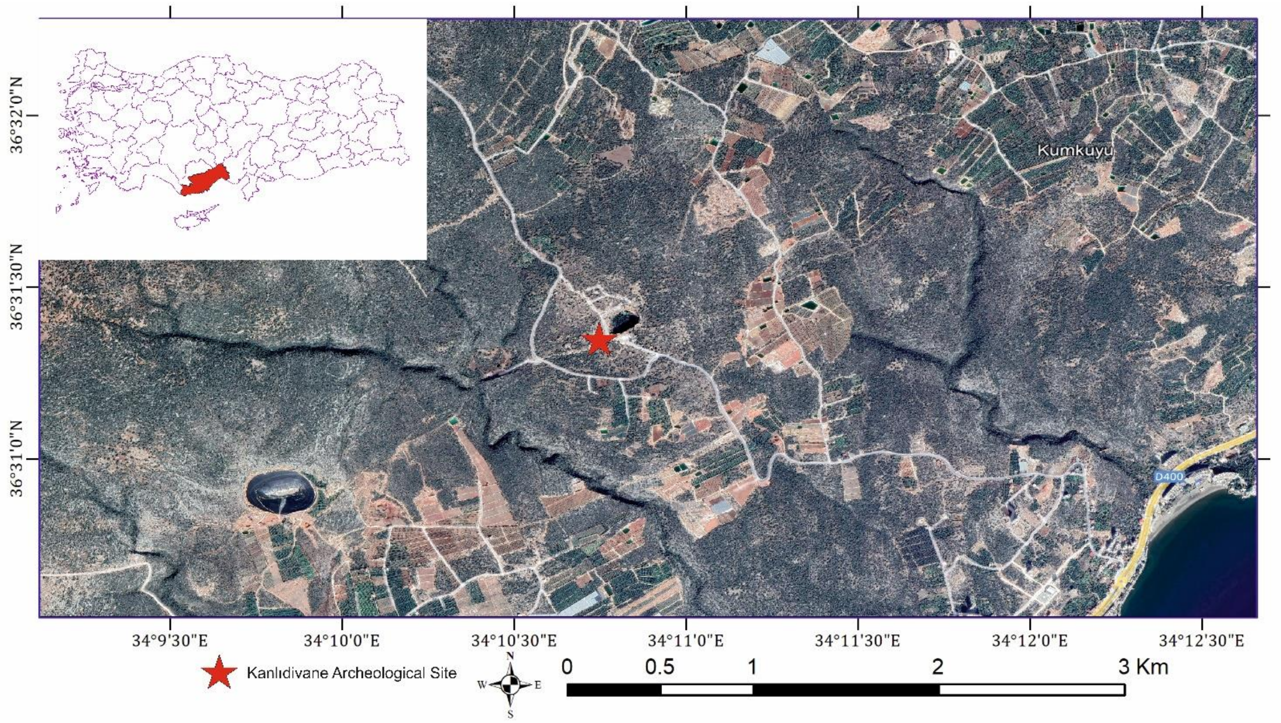


Figure 1. Location map of the study area

3. Method

In the first stage, the process of taking images of the mausoleum with an unmanned aerial vehicle was carried out. At this stage of the study, first of all, the necessary permissions for the flight were obtained. Images were taken manually with Parrot Anafi HDR drone around the tomb in the Kanlıdivane region (Figure 2).

In the second stage, the data taken from the unmanned aerial vehicle was transferred to the computer environment. Material deteriorations were examined from the images obtained, and they were processed on the chart prepared on the basis of classification of building elements. Based on the information in the chart prepared at the last stage, mapping was performed on the images and material deterioration was defined (Table 1).

Figure 2. Anafi Parrot

Table 1. Properties of drone

Feature	Value
Drone	
Size folded	244x67x65 mm
Size unfolded	175x240x65 mm
Weight	320 g
Max transmission range	4km with controller
Max flight time	25 min
Max horizontal speed	15 m/s
Max vertical speed	4 m/s
Max wind resistance	50 km/h
Service ceiling	4500m above sea level
Operating temperature	-10°C to 40°C
Lens	
Sensor	1/2.4'' CMOS
Aperture	f/2.4
Focal length (35 mm eq.)	23-69 mm (photo)
Depth of field	1.5 m - ∞
ISO range	100-3200
Digital zoom	up to 3x (4K Cinema, 4K UHD, FHD)
Photo resolution	21MP (5344x4016) / 4:3 / 84° HFOV

Table 2. Stone material deterioration on the facades of the monumental tomb structure

NATURAL STONE CONSTRUCTION ELEMENTS				PROBLEMS ENCOUNTERED ON CONSTRUCTION ELEMENTS MADE OF MASONRY MATERIAL IN BURDUR GAR																				
																						Faulty Repairs		
				Loss of surface	Fragmentation	Formation of gap/ hole	Pitting	Cracks	Exfoliation	Foliation	Discharge of jointing	Surface contamination	Shell formation	Efflorescence	Crystallization	Formation of plant	Formation of moss	Corrosion (Rust stain)	Tear	Loss of form	Colour change	Use of cement	Fall of plaster	Other
VERTICAL BEARINGS	SINGLE BEARINGS	Leg		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Column		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	CONTINUOUS BEARINGS	Wall		X	-	-	-	X	-	-	-	X	-	-	-	X	-	-	-	-	-	X	X	X
HORIZONTAL BEARINGS	FLOORINGS	Flat		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Curvilinear		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WALL OPENINGS		Window	Lintel / jamb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Sill	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Door	Lintel / jamb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Sill	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		Arch		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AUXILIARY ELEMENTS		Network		X	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
		Moulding																						
		Gargoyle																						
		Chimney																						
		Element for passage to the cover																						

4. Results

Based on the information in the chart prepared at the last stage, mapping was performed on the images and material deterioration was defined.

4.1. Material Deterioration in Single Carriers

In masonry structures, the only carriers are legs and columns. There are two pillars used in the building. The problems seen in the feet that make up the structure are in the form of scaling and color change caused by the effect of rain.

Figure 3. Scaling and discoloration of the feet

3.2. Material Deterioration in Continuous Carriers

In masonry structures, the continuous carriers are the walls. Material deteriorations on the walls were determined as surface loss, joint discharge, plant formations, and surface pollution. It has been determined that the rain water on the walls of the building causes material losses (surface loss) on the calcareous stone surface intensively as a result of the penetration of the rain water into the inner structure of the calcareous stone and its sudden evaporation due to sudden temperature increases in the geographical context. Rain water also caused the local mortar between the walls to melt, causing joint discharges. Plant formations are seen in these areas as a result of factors such as wind and various living things carrying plant seeds between the joints with the emptying of the joint spaces. In addition, there is an intense surface pollution caused by human-induced causes in the building. In order to destroy the bushes in the ancient city, the stubble burning processes in the immediate vicinity of the building, which the surrounding people removed, showed itself as a black layer on the stone material. In addition, there are serious cracks in the wall that divide the stone components into two. This graph shows a high probability of impact triggered by lateral thrusts or seating issues. As the monument is located very close to one of the geological discontinuity lines of the site, the danger of structural deterioration is confirmed by external forces.

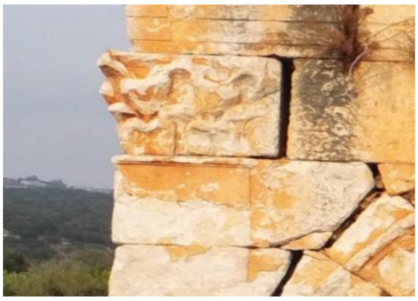
It has been determined that the structural body wall forming the south façade of the building is in the form of exfoliation, joint discharge, surface loss, surface pollution caused by human effects, crusting and fragmentation caused by the effect of rain (Figure 6).

On the eastern façade of the building, surface pollution caused by human-induced effects, joint discharge, plant formation, gap hole formation, surface loss and color change can be seen as a result of the effect of rain water on the stone. In addition, there are serious cracks in the wall that divide the stone components into two. This graph shows a high probability of impact triggered by lateral thrusts or seating issues (Figure 7).

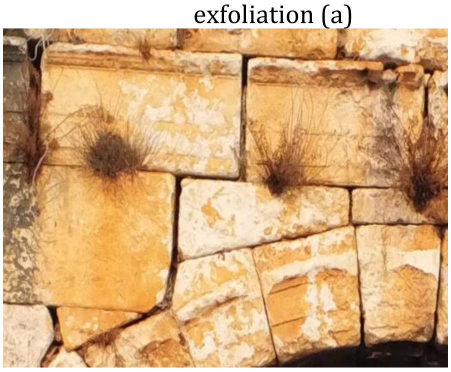
On the northern body wall of the building, there are serious cracks triggered by human-induced surface pollution, fragment rupture, joint discharge caused by rain, and lateral pressures or settlement problems (Figure 8).

On the eastern façade of the building, joint discharge, fragmentation, surface pollution, exfoliation and loss of surface stone material problems are observed (Figure 9).

exfoliation (a)



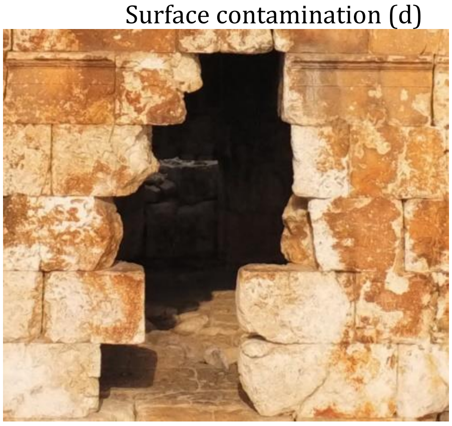
Joint discharge(b)



Plant (c)

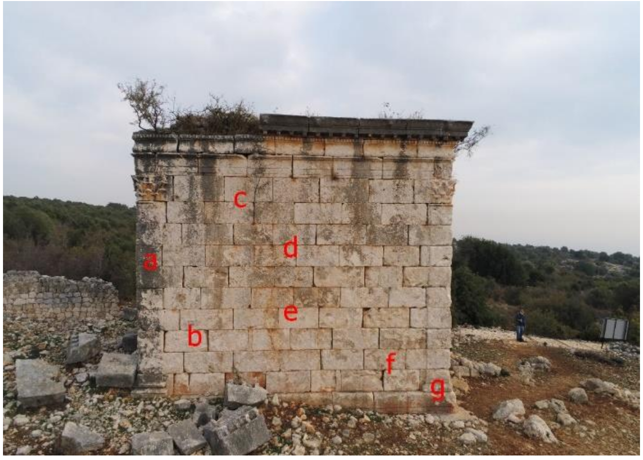
Surface contamination (d)

Soil crust(e)



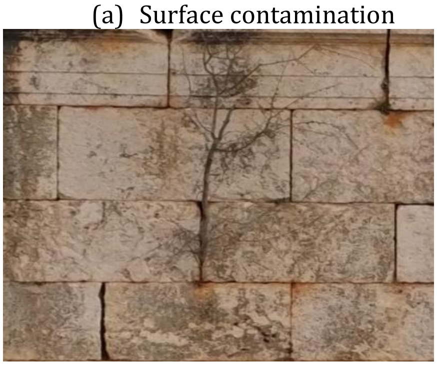
Chunking (f)

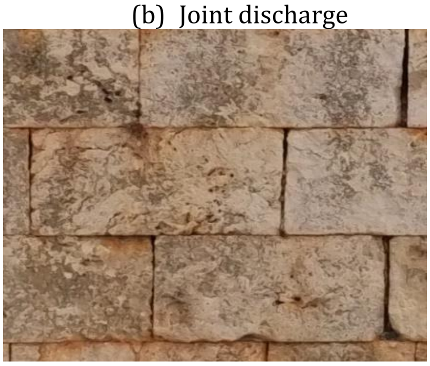
Figure 4. Material Deterioration on the Southern Front

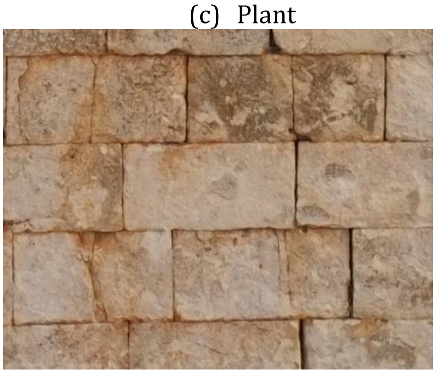


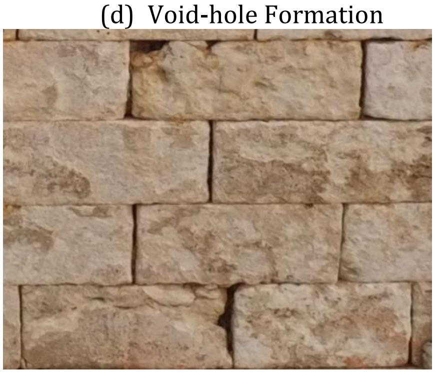

(a) Surface contamination


(b) Joint discharge


(c) Plant


(d) Void-hole Formation


(e) fracture


(f) Surface loss

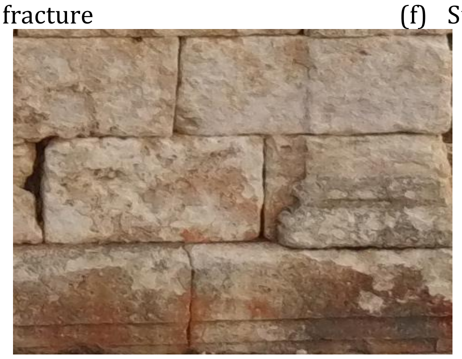

(g) Color change

Figure 5. Material Deterioration on the Eastern Front

(a) Surface contamination

(C) fragment rupture

(b) Fracture

(d) Joint Discharge

Figure 6. Material Deterioration on the Northern Front


(a) Joint Discharge


(b) fragment rupture


(c) Surface contamination


(d) exfoliation


(e) surface loss

Figure 7. Material Deterioration on the Eastern Front

3.3. Material Deterioration in Horizontal Carriers

In masonry structures, horizontal carriers are floors. Plant formations originating from the effect of water can be seen on the flat floor seen in the building (Figure 10).

Figure 8. Plant formation seen on the floor

3.4. Material Deterioration in Wall Cavities

The structural elements that make up the wall spaces in masonry structures are arches. The discoloration of the arches as a result of the joint discharge of the rain and the effect of the sun can be seen (Figure 11).

Figure 9. Joint discharge and discoloration in the arch

3.5. Material Deterioration in Auxiliary Elements

Building elements that make up auxiliary elements in masonry structures are moldings, ornaments and muqarnas. Surface pollution caused by human influence is observed in the wipes. Moisture-based plant formations were observed in places. On the other hand, it was determined that there were color changes in the decorations due to the effect of the sun (Figure 12).

Surface pollution in wipes, Plant formation

Color change in ornament

Surface pollution in decoration

Figure 10. Stone material deterioration in auxiliary elements

5. Discussion

In the study, it was aimed to detect and document the stone material deterioration of Mersin Aba mausoleum, which is a great necessity for the sustainability of cultural heritage, by using UAV photogrammetry. In the study, a deterioration map could be generated from the data obtained by UAV photogrammetry to support restoration analysis quickly and easily, thanks to their high resolution. According to this result, it is seen that the UAV photogrammetry method can provide images with sufficient resolution for the detection of material deterioration of stone structures. This result supports the fact that it is easily possible to model buildings from close range or to control material deterioration using UAVs obtained in various studies in the literature [48-51].

In addition, with this method, it has been achieved that it provides a higher data collection rate than the traditional method and provides a better representation of the material and material problems. This result supports the fact that the use of UAVs equipped with commercial cameras obtained in various studies in the literature provides lower vehicle cost, higher data collection speed, and most importantly, a better representation of materials and material problems [44-46].

Another finding is that the material problems can be easily detected from the images obtained with the unmanned aerial vehicle without examining the structure in the field. Remondino et al. [47] and Cavalagli et al. [51] found that UAV photogrammetry is also one of the best solutions to overcome terrain limitations and investigate facade areas that are hidden or inaccessible from the ground, and that such a methodology can be used to investigate inaccessible structures and damage historical masonry structures and supports the conclusion that it is very effective for quantitative estimation.

Another important finding was that as a result of the study, images of the facades were obtained in orthophoto to investigate the material deteriorations on the facade and the deteriorations on the facade could be mapped. This finding supports the conclusion of Russo et al. [2] that it is possible to obtain a metric orthophoto image of the facade of a historic building of suitable quality for a detailed mapping of stone material deterioration on the facades.

Another finding was that the most common stone material deterioration types in the building were surface pollution, cracks and exfoliation. According to this result, it is seen that the assessment of structural damage by photogrammetric research with UAVs and especially cracks, microcracks and material shortages can be mapped without direct access, and this can be done based on virtual visual inspection. This result supports the results obtained by Cavalagli et al. [51], that even the types of material problems can be determined based on the smallest detail, based on virtual visual inspection only, thanks to UAV photogrammetry, without examining the structure in situ with UAVs.

6. Conclusion

The Aba mausoleum, located in the ancient city of Mersin Kanlıdivane is one of the most well-known places in the region. The data obtained in the results of the study showed that, thanks to their high resolution, a deterioration map can be created quickly and easily to support restoration analysis.

Although the architectural integrity of the building was partially preserved in the findings obtained as a result of the study, it was observed that there were material deteriorations and structural deformations, especially on the west and north walls. There are serious cracks in the north wall that divide the stone components into two. This indicates a high probability of impact triggered by lateral thrusts or settlement issues. Since the monument is one of the few examples of architectural and structural integrity that still exists, it should be included in the architectural preservation program as soon as possible before it loses its structural integrity.

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Author contributions

Lale Karataş; Methodology, data collection, writing **Aydın Alptekin;** Writing, Control. **Murat Yakar:** Editing the manuscript

Conflicts of interest

The authors declare no conflicts of interest.

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