STRATEGIC PLANNING OF MATERIALS AND CONSERVATION INTERVENTIONS FOR THE DAMAGE REHABILITATION OF THE SARANTAPICHO ACROPOLIS AND THE Erimonkastro Acropolis in Rhodes

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ABSTRACT

In this work, GIS modeling and analysis operations are utilized to accomplish strategic planning of materials and conservation interventions, for the damage rehabilitation of the Sarantapicho Acropolis and Erimonkastro Acropolis in Rhodes, Greece. GIS thematic maps were developed presenting characteristic parts of the walls of the two Acropolises. Orthophotos were used as the GIS base-map, whereas materials and decay data, collected after the application of non destructive testing and evaluation techniques in situ and analytical techniques in lab after sampling, comprised the attribute data sets which describe the characteristics of the spatial entities. This resulted in the development of building materials and decay thematic maps. Moreover, attribute databases consisting of data of physicochemical characteristics were built and linked with the internal database file of the corresponding GIS materials/decay mapping project of the Acropolises walls. Finally, using geoprocessing analysis the conservation intervention thematic map was produced, where attribute data from both materials and decay themes were incorporated into the new output theme, contributing to the strategic planning of materials and conservation interventions, for the damage rehabilitation of the Sarantapicho Acropolis and Erimonkastro Acropolis. It is concluded that GIS modeling and analysis operations of the developed materials/decay/conservation interventions thematic maps along with the corresponding relational databases, can contribute decisively to the monuments monitoring, as well as to the management and control of building materials life cycle.

1. INTRODUCTION

The classification and representation of monuments pathology aims to control the decay progress and to improve planning of conservation interventions. This can be accomplished through the recording and presentation of building materials, developed decay patterns and their extent, on architectural drawings [1]. The use of electronic means and their special tools can achieve, in a modern and effective way, control of monument pathology and its life cycle, cost analysis, pointing towards monument protection through prediction and prevention [2]. Therefore, GIS modeling and analysis operations are more and more often used for the above mentioned purposes, due to their special capabilities regarding the processing of different background data which incorporate spatial and attribute (descriptive) data sets. Thus, within the framework of the preservation of cultural heritage, many scientific projects have investigated GIS potential for the conservation and protection of historic buildings and archaeological sites [3, 4], as well as for the rehabilitation and urban development of historic cities centers [5, 6].

In the present work, GIS is utilized for developing materials/decay/conservation interventions...
thematic maps about the archaeological sites of the Sarantapicho Acropolis and the Erimokastro Acropolis in Rhodes, Greece. GIS capabilities of recording, grouping, managing and analyzing large volumes of spatially referenced and associated attribute data, along with decay diagnosis results, were used for the elaboration of data bases and spatial data transformation and analysis, aiming at the monitoring and preservation of both archaeological sites.

Both archaeological sites (Fig.1) are located in natural fortified areas at the northeastern part of Rhodes island. In particular, the Acropolis of Sarantapicho, is not an established archaeological site, even though there is strong evidence that it was protected by cyclopean walls of the Mycenaean period, and their remains are still evident throughout the site [7]. The use of the building material of the ancient walls from a nearby lime industry indicates that rigorous actions must be adapted by local and central authorities in order to protect the site. The Acropolis of Erimokastro (Deserted Castle) is an established archaeological site, located at a natural hill between Kallithea and Afantou bays. Its dry-stone walls are multifaceted and possibly of cyclopean type, 2-4m high and 1,7 – 2m wide [7].

![Fig. 1: Representative photos (a) of the wall of the Sarantapicho Acropolis, (b) of the wall of the Erimokastro Acropolis, (c) of the entrance of Erimokastro Acropolis](image)

2. EXPERIMENTAL

The GIS thematic maps which were elaborated, present characteristic parts of the walls of the two investigated Acropoles. In situ taken photos were geometrically corrected in lab by digital photogrammetric software (Archis of Siscam) resulting in orthorectified images. These orthophotos were imported in CAD environment (AutoDesk 2006) in order to produce the linework which functioned as the blueprint for the GIS base-map in ArcMap/ArcInfo 9.2 [8].

In parallel, during diagnostic study, non destructive testing and evaluation techniques were applied in situ, whereas analytical techniques were used in lab after sampling, resulting in building materials characterization and decay diagnosis for both investigated sites [9]. In addition, materials and conservation interventions were suggested according to the results of the integrated diagnostic study [9]. The non destructive testing and evaluation (NDT & E) techniques applied in situ were ultrasonics, ground penetrating radar, infra-red thermography and fibre optics microscopy; whereas the analytical techniques used in lab after sampling were X-ray diffraction, optical microscopy, scanning electron microscopy, mercury porosimetry, determination of the total soluble salts content and mechanical testing.

Building materials, decay patterns and conservation interventions data, comprised the attribute data sets which describe the corresponding thematic maps features. Moreover, these data were used for building the relational data bases in .dbf file format, in order to store the attribute data of the thematic map features.
3. RESULTS & DISCUSSION

3.1. Summary of diagnostic study results

The results of the diagnostic study (after NDT&E techniques in situ application and analytical techniques utilization in lab after sampling), showed that the building material of the Sarantapicho Acropolis is a grey fossiliferous limestone of 0.5-1% porosity; whereas the building materials of the Erimokastro Acropolis are a grey compact limestone of ~1% porosity which presents, at low extent, grey-brown inclusions of calcite rich hornstone with low porosity of ~ 0.5%, as well as an off-white porous fossiliferous limestone of ~6% porosity [9].

In parallel, the presented decay patterns in all type of stones of both archaeological sites can be summarized as following [9]:

1. Extended biodecay mainly attributed to (a) the extensive growth of crustose epilithic lichens of grey-white and brown-orange coloring, (b) the extensive growth of fungi that result in the extended grey-black coloring and the limited and localized black coloring of the stone surface, and (c) the development of biopitting, microcracking and pollen grains.
2. Cracking, holes and cavities are present, indicating loss of stone material, along with multiple scaling, detachment and delamination of stone material.

In addition, in the Erimokastro Acropolis, the grey-brown quartz inclusions of grey compact limestone present intense superficial fracturing due to extensive growth of fungi mycelia that penetrate vertically the main body of the stone and biopitting. Moreover, the off-white porous fossiliferous limestone presents alveolar disease due to salt crystallization at the interior of the stone. Building materials and decay patterns of both investigated archaeological sites are depicted in Fig. 2.

![Fig. 2: Representative Photos of the walls of the Erimokastro Acropolis (left) and the Sarantapicho Acropolis (right), showing the building materials and decay patterns](image-url)

Furthermore, according to the materials characterization and decay diagnosis for both archaeological sites, the following conservation interventions are suggested:

1. application of lithium hypochlorite water solution for the removal of crustose epilithic lichens,
2. application of ampicillin water solution for the removal of fungi,
3. application of methyl-sulfonic pyridine water solution whose biocide action act as a protective agent against lichen and fungi growth.

After controlling and constraining the biodeterioration for all stone types presented in both sites, it is suggested: (a) the application of a water soluble epoxy-acrylic copolymer for filling up the presented cracks in the case of the grey limestones of both sites; (b) the repeated application of
paper pulp with deionized water for the extraction of soluble salts from the off-white porous fossiliferous limestone and afterwards the application of a prehydrolyzed ethyl silicate based material, for its consolidation; and (c) the application of a siloxane based material, for the protection and consolidation of the superficial fractures presented on the grey-brown quartz inclusions of the grey compact limestone in Erimokastro acropolis.

3.2 Development of Building Materials - Decay Thematic Maps and Database

3.2.1 Methodology

The GIS thematic maps which were elaborated, present a characteristic part of the walls of Sarantapicho Acropolis, a characteristic part of the walls of Erimokastro Acropolis, as well as a part of the entrance wall of the Erimokastro Acropolis. The orthophotos of these three characteristic parts of the walls of the investigated sites were used as the GIS base-map, where data elements in space were recorded. In parallel, the data collected after the application of non-destructive testing and evaluation techniques in situ and analytical techniques in lab after sampling comprised the information about building materials and decay patterns.

During spatial data input in ArcMap/ArcInfo, the process of topology building is of high importance. The topology building is necessary for the creation of spatial relationships among features of the same layer; that is for the construction of digital relationships which would be identifiable in a thematic map and are related to connectivity, contiguity and adjacency [10, 11]. Moreover, building a layer topology requires recording and attributing of descriptive characteristics to the spatial entities/features that constitute this under construction layer. Thus, topology building, in addition to building spatial relationships among features which configure a layer, is directly related to the recording and storing of the corresponding attribute data sets that describe real world entities or conditions [10, 11].

Building materials and decay patterns data comprised the attribute data sets which describe the characteristics of the recorded spatial entities of both investigated sites. Therefore, ascribing the materials and decay results of the diagnostic study to the features of the GIS base map, during building topology, led to the development of the thematic maps of building materials and decay (Fig. 3, 4).

Each building material/decay pattern was classified according to its spatial properties and physico-chemical characteristics, and was represented by a different layer and displayed by a different color. So, in both thematic maps of Erimokastro (fig. 3, 4) the elaborated layers were classified and mapped regarding: (a) the materials of grey compact limestone (depicted by brown color), grey-brown quartz inclusions (red color), and off-white porous fossiliferous limestone (light green color); as well as (b) the decay patterns of white-grey crustose epilithic lichens (depicted by beige color), brown-orange crustose epilithic lichens (orange color), fungi biodecay (hatched dark green and black color), superficial fracturing due to fungi growth (light orange color), holes and cavities-loss of stone material (yellow color), cracks (black color), flora (green color) and alveolar disease (grey color). It is worth mentioning though, that in both thematic maps four more layers, not related to materials and decay, were built. These layers’ recording was of high importance in order to reproduce from orthophotos the base-map linework correctly. These layers were displayed by hatched colors and are the following: stone contour, lateral carving surface, external surface of voids in the dry-stone wall, and stones filling the irregular spaces between the basic building stones.
In the case of the Sarantapicho thematic map corresponding layers classification and mapping was performed, with the exception of the material layer which was the one of grey compact limestone (depicted by brown color), whereas regarding the decay layers, alveolar disease and superficial fracturing due to fungi growth were not included, since they were not identified by the diagnostic study.

Moreover, an attribute database consisting of physicochemical characteristics data was elaborated and linked to the attribute table of the corresponding GIS materials/decay/mapping project of the Acropoles walls, thus resulting in a relational database. In particular, the GIS attribute table, which includes topological characteristics like perimeter, area, adjacency info etc was linked with an external database where data regarding petrography, mineralogical composition (results of polarizing microscopy and X-ray Diffraction), total porosity, specific surface area, apparent density, average pore radius (mercury porosimetry results) and total soluble salts content, were stored and classified. The database was built using text and numerical elements as type of entries; whereas the data fragmentation permits the user to interrelate data regarding materials characterization, and decay diagnosis with the vector data, locating the info in a geometrically exact point or area, respecting the topological relationships among the various parts of the Acropoles walls [10, 11]. This is possible since the first field of the above mentioned database is flagged with the same identification code as the topological element to which the descriptive data refer to and the user can view the information, whenever the corresponding themes are active.

3.2.2 Results
Data retrieval is accomplished by the use of the relational operators that the GIS platform provides in order to compare values associated with spatial data [10]. Boolean operations (logical combinations of data, involving union, intersection, complement and exclusion), as well as logical operations (like equal to, greater than, etc) were used for different entities and attributes access, manipulation and analysis. As shown in fig.3 the geometric entities that comply with the combined expression of logical and Boolean operations of “total porosity less than 1 AND average pore radius greater than 1” are highlighted on the map and on the database with light blue colour. Furthermore it is demonstrated, by the database highlighting, that only the material of grey-brown quartz inclusions satisfy the defined logical and relational criteria, a fact that reflects the dynamic and direct interrelation of the database to the vector data.

In addition, in fig. 4 demonstrates the GIS capability to extract the area of the identified features that satisfy the combined expression of logical and Boolean operations of “decay equal to grey-white crustose epilithic lichens AND material equal to grey compact limestone”. The GIS software capability to extract the area of spatial entities selected by attributes is a classification process that can provide valuable info concerning the extent of building materials and presented decay patterns. Comparison and correlation of the retrieved data, can point out critical issues on building materials susceptibility to decay in relation to environmental parameters on real scale.
Fig. 3: GIS analysis operations on materials and decay thematic map for the entrance of the Erimokastro Acropolis

Fig. 4: GIS analysis operations on materials and decay thematic map for the wall of the Erimokastro Acropolis
Therefore, the comparative diagram (fig. 5) of the area of the presented decay patterns for the wall of the Sarantapicho Acropolis (expressed as the percentage of each decay pattern on the total mapped area of the wall) shows that grey fossiliferous limestone is more susceptible to the growth of crustose epilithic lichens (especially the grey-white coloured ones) than to fungi biodecay, whereas loss of stone material is of low percentage. Additionally, the corresponding comparative diagram of the area of the building materials present in the entrance and the wall of the Erimokastro Acropolis (fig. 6), demonstrated that grey compact limestone is the most frequently building material used in both mapped areas, whereas off-white porous fossiliferous limestone holds relatively high coverage on the wall of the Erimokastro Acropolis compared to the mapped area of the Erimokastro Acropolis entrance. Grey-brown quartz inclusions cover a low percentage in both cases.
Finally, the comparative diagram (fig. 7) of the area of the presented decay patterns for the entrance and the wall of the Erimokastro Acropolis showed that grey compact limestone is more susceptible to the growth of fungi biodecay than to crustose epilithic lichens in both investigated areas. Grey-white crustose epilithic lichens presented higher percentage values in northeast oriented Erimokastro entrance, whereas brown-orange coloured lichens presented higher percentage values in northwest oriented wall of Erimokastro Acropolis.

Off-white porous fossiliferous limestone presented higher susceptibility to alveolar disease and to loss of stone material (which is also attributed to salt crystallization process) at the northeast oriented entrance wall, whereas northwest oriented wall displayed higher percentages of both biodecay types (fungi and lichens). In addition, grey-brown quartz inclusions of grey compact limestone presented high susceptibility on superficial fracturing due to fungi growth on both investigated sites, whereas only brown-orange crustose epilithic lichens are present on the northwest oriented wall of Erimokastro Acropolis.

3.4 Development of Conservation Interventions Thematic Map
3.4.1 Methodology

Using geoprocessing analysis and in particular the intersection operation tool for both materials and decay thematic maps, the resulting output theme is the conservation intervention thematic map. This output theme includes features with attribute data from both input and overlay themes (materials and decay themes respectively). Therefore, the new thematic map of conservation interventions contains combined spatial information and the aggregation of the attribute data of both materials and decay thematic maps.
Even though, the resulting features include combined spatial properties and attribute data of both materials and decay thematic maps, they were additionally classified according to a new attribute data set regarding the suggested materials and conservation interventions; data which were based on the outcome of the diagnostic study. Therefore, the developed conservation interventions thematic maps of both investigated sites, present spatial entities which hold spatial properties and attributes of the materials and decay themes, as well as new spatial properties and attributes related to the suggested materials and conservation interventions, thus incorporating the total gathered evidence of the diagnostic study.

Consequently, each material and conservation intervention was represented by a different layer and displayed by a different color in both the conservation interventions thematic maps of Erimokastro (fig. 8, 9), and the conservation interventions thematic map of Sarantapicho (fig. 10). The new elaborated layers comprise features and attributes concerning building materials, decay and conservation interventions.

3.4.2 Results
Data retrieval is also accomplished in the conservation intervention thematic maps by the use of the relational operators that the GIS platform provides in order to access, manipulate and analyze different entities and attributes [10]. As shown in fig. 9 the geometric entities that comply with the combined expression of logical and Boolean operations of “conservation intervention equal to ampicillin water solution AND material equal to grey-brown quartz inclusions” are highlighted on the map and on the database with light blue colour. Furthermore it is shown, by the database highlighting, that the decay of “superficial fracturing due to fungi growth” is the decay pattern that the required conservation intervention (that is the ampicillin water solution), for the required material (that is grey-brown quartz inclusions), is applied for.
Similar results regarding data retrieval are obtained by the utilization of GIS relational operators on the conservation interventions map of Sarantapicho Acropolis (fig. 10). In particular, the identified features that satisfy the combined expression of logical and Boolean operations of “conservation intervention equal to lithium hypochlorite water solution AND decay equal to brown-orange crustose epilithic lichens”, are selected and highlighted on the map and on the database with light blue colour. In parallel, in the highlighted entries of the database the building material that corresponds to the required conservation intervention and decay is presented (that is the grey fossiliferous limestone). These procedures demonstrate in practice the incorporation and interrelation of attributes related to building materials, decay and conservation interventions to the vector data in the conservation interventions thematic maps for both investigated sites.

Moreover, cost analysis of conservation interventions can take place utilizing the GIS software capability to calculate the area of spatial entities selected by the attribute of a required conservation intervention. Knowing the exact area of each conservation intervention and the consumption of the applied materials it is possible to perform an accurate cost analysis of the conservation intervention works in the investigated wall surfaces and consequently estimate the cost of the conservation intervention works in total for both Acropoles.

It is clear that in the case of the application of the suggested conservation interventions in the future and when the attribute database is enriched by the new evidence regarding the assessment of the critical performance characteristics of conservation materials and interventions, and utilizing the GIS geoprocessing analysis, scientists have the opportunity of controlling and monitoring (a) the preservation state of the investigated wall surfaces, and (b) the decay susceptibility of the building materials, and consequently their durability. Thus, the use of a GIS platform can create an information management system where data sets concerning building materials, decay and conservation interventions are recorded, correlated, distributed, analyzed and attributed to space, during different time periods, contributing decisively to the strategic planning of periodical conservation interventions, in relation to environmental parameters on real scale.
Fig. 9: GIS analysis operations on conservation interventions thematic map for the entrance of the Erimokastro Acropolis

Fig. 10: GIS analysis operations on conservation interventions thematic map for the wall of the Sarantapicho Acropolis
4. CONCLUSIONS

Diagnostic study results concerning building materials and decay data were recorded and attributed to both investigated Acropoles spatial entities, resulting in the development of GIS thematic maps, which after the use of GIS operational analysis provide valuable info regarding (a) the extent of building materials and presented decay patterns, (b) critical issues on building materials susceptibility to decay in relation to environmental parameters in real scale. Finally, geoprocessing analysis of the developed building materials and decay thematic maps lead to the conservation interventions thematic maps, upgrading the conservation interventions through the incorporation of spatial and attribute data regarding building materials, decay and conservation interventions, contributing to the strategic planning of conservation interventions of both investigating sites.

It is concluded that GIS modeling and analysis operations of the developed materials/decay/conservation interventions thematic maps along with the corresponding relational databases, can contribute decisively to the monuments monitoring, as well as to the management and control of building materials life cycle.

REFERENCES