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NON-DESTRUCTIVE METHODS FOR EVALUATION OF THE STATE OF PRESERVATION IN HISTORICAL STONE MONUMENTS: THE CASE STUDY OF THE STEP PYRAMID IN SAQQARA

Agnese Kukela, Valdis Seglins

University of Latvia, 10 Alberta street, Riga, LV-1010, Latvia, e-mail: agnese.kukela@lu.lv, valdis.seglins@lu.lv

Abstract

This study aims to facilitate visual interpretation of the photo documentation data by evaluation of the 3D model of the Step Pyramid of Djoser using MicroStation V8i software. The integration of the data into the 3D model allowed to make number of conclusions regarding the structure of the Step Pyramid, potential threats to its stability, stone material used for the construction of the pyramid and differences in quality of the mortar applied. The results of this study denote high potential of this methodology for its application in preliminary studies of stone monuments on Memphite necropolis area to contribute the elaboration of future preservation and conservation strategy.

Key words: Step Pyramid, geospatial model, weathering, stone material damage

INTRODUCTION

All stone monuments, irrespective of the building material and its initial quality, are exposed to the environmental impact affecting their state of preservation. Generally, stone monument studies are aiming to determine potential threats and to facilitate the elaboration of appropriate monument conservation strategy. Most of the existing weathering assessment methods and classifications are time consuming, expensive and require direct contact with the surface for application of instrumental investigations or to take samples for analysis. However, these methods can be adjusted and developed as non-destructive by creating custom classification of weathering forms and their intensities using detailed monument photo documentation data.

MATERIALS AND METHODS

This study is based on detailed photographic documentation of the Step Pyramid carried out repeatedly during 2005–2011. The images acquired were processed and integrated into the geospatial model of the pyramid (Seglins *et al.*, 2011) for further analysis and interpretation. The processing of the data and creation of photo mosaic was performed manually, thus ensuring high precision and quality of images selected from the electronic archive of photographic documentation (more than 3500 high resolution images), which formed the main data array (Fig. 1). The elaborated layer of photographic documentation covered the exposed surface of all four facades of the pyramid and by the means of MicroStation V8i software enabled us to perform interpretation of each point of the pyramid's facade with 2 mm precision. In the current study, this was the basic information layer, which was further interpreted, modified and supplemented with other information layers containing the data allowing us to integrate this information into the 3D model.

The priorities of the study of the data registered in the versatile photographic documentation were set according to the damages of the pyramid's structure macroscopically identified *in situ*. Such damages are cracks and faults visible on the facades of the pyramid, damages of the exposed surfaces of stone material (further referred as weathering) and loss of binding material. Other types of damages, including those accruing from earlier conservation and restoration works, were identified too. However, their importance in respect to the general stability of the monument is less significant.

To diagnose various weathering types and their intensities several studies were performed in the ancient monuments of Saqqara and Giza plateaus, in Dahshur and Old Cairo. Additional comparative studies were carried out on areas previously studied by Bernd Fitzner, applying instrumental methods for identification of physical and mechanical properties of weathered stone material (Fitzner *et al.*, 2002). In these particular areas, studied by B. Fitzner, comparative tests were performed aiming to correlate the data obtained by instrumental measurements with the data obtained from the analysis of photo documentation (Kukela & Seglins, 2011). However, in order to approbate and adjust this methodology to make it applicable in Saqqara, some additional classifications for detailed analysis in several particular sample areas were developed. An example of such detailed stone material weathering map is shown below (Fig. 2). The results of this adjustment allowed us to develop and approbate the scale of stone material weathering and its intensity diagnosis which was further applied in the studies of the facades of the Step Pyramid.

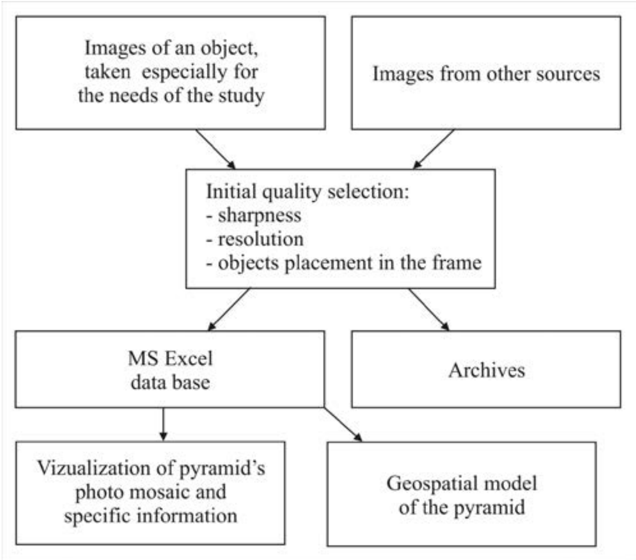


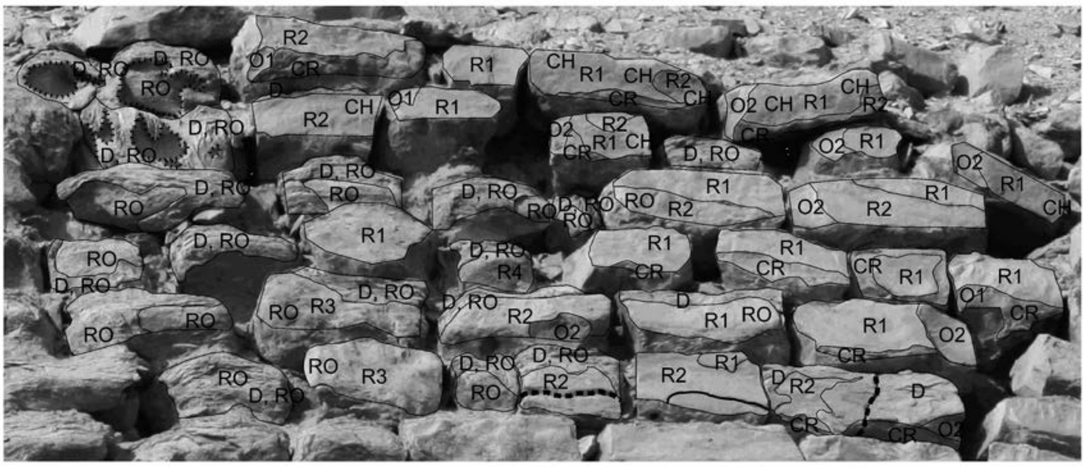
Fig. 1. Schematic depiction of management of the photo documentation.

To assess the exposed surface of stone material in all the facades of the Step Pyramid, after numerous approbations and adjustments, a single unified catalogue was developed and applied (Kukela & Seglins, 2012). This catalogue included three the most widespread weathering types (rounding, surface detachment and loss of stone material) and each of these weathering types were given the assignment of five degrees of intensity, measuring from 0 to 4. Applying the aforementioned stone material weathering classification, the photo documentation information layer integrated into the geospatial model of the Step Pyramid was analysed manually, identifying weathering types and their intensities on all four facades of the pyramid (altogether 11938 m^2) with the degree of detailed elaboration of 0.25 cm^2. The precision of the attachment of study area to the 3D model was in the range of 0.5 m^2. However, the application of such catalogue is not always unequivocal, moreover in case if the quality of photo documentation is rather low and an option to verify the weathering types and their intensities on site is not available.

RESULTS

By analyzing photographic data obtained starting from the year 2005, three main stone material weathering forms and five weathering intensities were identified on all four facades of the Step Pyramid and further depicted on the geospatial model of the pyramid (Fig. 3). Particular weathering forms were set as the main features, but weathering intensities – as supplementing ones.

Grey and yellowish grey layers of sandy limestone of the Saqqara plateau, formed by Middle Eocene Mokkatam Formation as layered and rhythmic lime rocks at shallow sea conditions is the main building material in this area that has been used in construction of the necropolis. The stone material, mostly limestone with different admixture of sand and clay (Klemm & Klemm, 2010), affected by rounding is mechanically durable, but the edges of the stone blocks were rounded due to wind carried sand particles. The stone mate-



Weathering forms	Abbreviation/Intensity
Chemical changes	CH
Changes in relief	R / R1, R2, R3
Detachment of layers	D
Fragment break off	O / O1, O2
Crumbly loss of material	CR
Rounding	RO

Weathering forms	Designation
Cavern	(dotted oval)
Split	(dashed line)
Fissure	(solid line)

Fig. 2. Weathering intensity map. The fragment of the Step Pyramid's southern facade.

Table 1

Stone material surface detachment and loss of stone material weathering types on the facades of the Step Pyramid, percentage of the area of a facade

Surface detachment and loss of stone material weathering types	Southern facade %	Eastern facade %	Northern facade %	Western facade %
1st step	42.45	30.18	61.51	20.55
2nd step	60.34	60.31	55.91	50.81
3rd step	59.82	70.00	57.90	62.50
4th step	41.41	73.69	60.64	70.38
5th step	50.89	69.23	53.13	95.12
6th step	70.87	67.21	50.72	100.00
Total on the facade	49.78	50.36	58.69	39.96

rial affected by surface detachment weathering type is less durable, lower quality, but still visually similar to other stone blocks. The rest of the blocks, whose surface weathering was accessed, indicate the loss of stone material. Initially, these blocks had inner cracks, which were not identified while choosing this building material; therefore the block fragments are crumbling. Such visualization of data provides significant information about the damages of the pyramid's facades, the volume of necessary renovation work and the state of its urgency.

The results of visual analysis demonstrate that none of the weathering types or their intensities is predominant on any of the facades of the pyramid. Similarly, any particular weathering type or intensity can not be attested to any particular step of the pyramid. This statement is also confirmed by statistical analysis (Table 1), which is an additional option resulting from the integration of the data into the geospatial model.

Table 2

Distribution of weathering intensities on the surface of the Step Pyramid, percentage of the area of a facade

Weathering intensity	Southern facade %	Eastern facade %	Northern facade %	Western facade %
0	0.20	0.23	0.11	2.15
1	8.11	12.35	16.57	18.23
2	18.86	24.25	22.23	15.87
3	35.82	19.24	29.13	15.63
4	17.93	27.07	16.32	12.59

Regardless of the complicated distribution of different weathering types on the pyramid facades, the total area affected by weathering varies. On the southern facade of the pyramid surface the detachment and loss of stone material of the exposed stone blocks have affected 49.78% (1709.70 m^2) of the surface. On the proximal eastern facade these weathering types affected 50.36% (1213.30 m^2); on the western facade – 39.96% (1145.74 m^2) and on the northern facade – 58.69% (1893.77 m^2). On the other hand, a rather common weathering type expressed by rounding is spread quite evenly and the areas affected by this type of weathering vary between 25–33%.

Additional information and knowledge is provided by the weathering intensity expressed in weathering intensity categories from "0" (weathering traits are slightly visible on the surface of the stone block) up to "4" (damage caused by weathering has changed the exposed surface of the stone block and severely affected stone material) (Table 2).

The data demonstrates that predominant weathering intensities are "2" and "3" (Table 2). Overall it is an indication of quite high degree of knowledge of ancient builders regard-

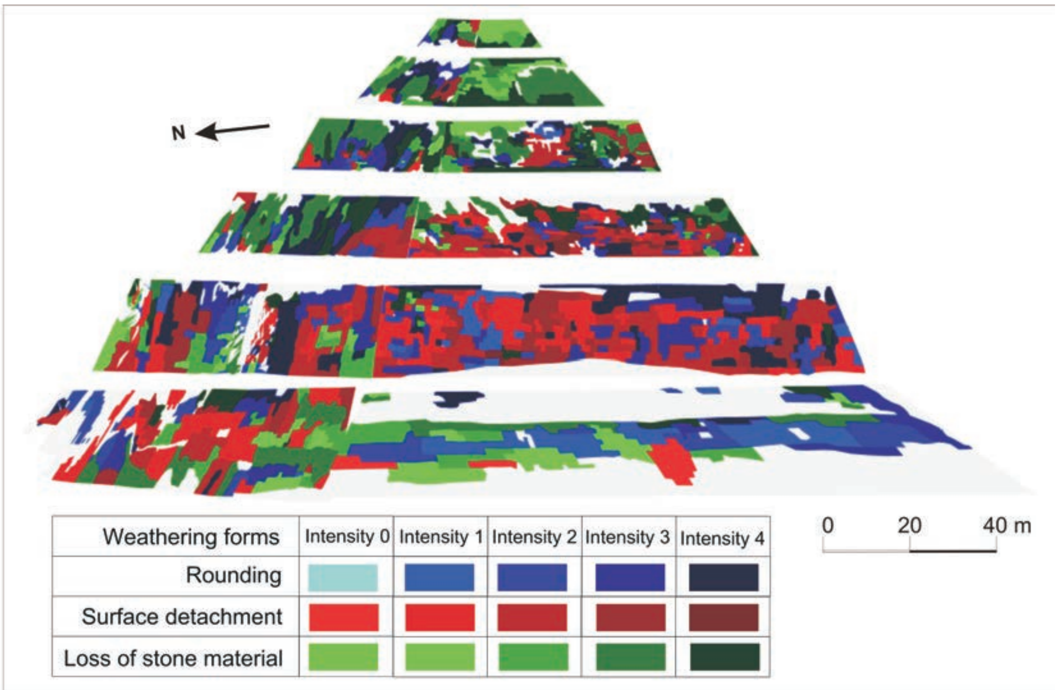


Fig. 3. Visualization of weathering types and their intensities on the facades of the geospatial model of the Step Pyramid.

Fig. 4. Schematic depiction of possible construction stages of the Step Pyramid, characterising various quality of the stone material used (different quality material is marked as "1", "2", and 3").

ing the choice of the construction material. Yet, the eastern facade, where weathering intensity "4" forms 27.07% of the whole area of the facade, is an exception. This is the facade where on the first two steps initial stages of the pyramid's construction are exposed (Lauer, 1962) and construction blocks are elaborated less accurately. This also is fortified by significant loss of cement mass and its comparatively low quality in that area.

The photo documentation itself can provide a peculiar outlook on the construction process of the pyramid. Detailed analysis allows us to identify the peculiarities of the construction process of individual steps of the pyramid. Results

Fig. 5. Step Pyramid's reconstruction process. Eastern facade in the year 2012.

of simplified assessment of the quality of construction blocks and their resistance to weathering in general are schematically demonstrated and denote to several supplies of the material of different quality (Fig. 4). Scree layers and recently reconstructed areas of the pyramid were excluded from this assessment.

This data demonstrate that during the pyramid's construction process only a part of the building material was accumulated on the construction site; the other part was delivered upon necessity from different limestone quarries, situated in the vicinity of the Step Pyramid complex (Welc, 2011) and escarpment quarries of the Saqqara plateau. The speed of stone material provision was not sufficient in comparison to the speed of construction. This could explain why along with high quality construction blocks, lower quality material was used. Should this be confirmed, it could indicate that the main core of the pyramid would consist of low quality material and due to economical reasons some parts would be filled up with debris or even left empty.

To establish possible construction sequence of the pyramid, to identify the areas of ancient reconstructions work and to perform detailed stone material and mortar analysis, additional investigation would be necessary. However, such studies are currently impossible and, apparently, will not be possible in the nearest future due to vast reconstruction currently in progress (Fig.5), which has defaced all these important indications.

DISCUSSION

Most ancient monuments are studied by different specialists and scientific publications are oriented towards particular issues concerning the object, e.g. architecture, iconography, historical consequence, etc. Despite of their significance, such publications do not yield the possibility to make general conclusions about the monument, which are necessary to set the priorities for its preservation. For instance, the Step Pyramid of Djoser has been largely studied (Firth & Quibell, 1935; Lauer, 1962, Baud, 2002, Lehner, 2004, etc.) and these studies detected numerous recognizable damages of the monument, yet their spatial distribution and interconnectedness have been developed to a small extent. Therefore, organization of the data and various observations in a geospatial model with an option to maintain Geographic Information System (GIS) data base is methodologically a significant aspect.

Additionally, since some of the specific studies, such as detection of stone material weathering or studies of mortar, contain the elements of subjectivism, it is important, that the basic information layer contains high resolution photographic documentation only. Such approach allows us to minimize the prejudice opinion during the interpretation and enchain the data to particular geospatial point of an object. This ensures the possibility to range the material according to its credibility and in case of any doubts allows us to perform additional verifications of particular information on a precise area *in situ*.

The classification applied for the diagnostics of stone material and mortar weathering should be adjusted, modified and simplified if necessary, depending on the particularities of the monument and data source available. The degree of detailed elaboration during the process of visualization of the results depends on the purpose of the study. It can be carried out for each of the stone blocks in particular areas or for the whole structure in a larger scale.

Additionally, the data on the specific character of the monument's construction process and identification of the building material used is essential for correct determination and prognostication of degree of stability of the monument.

Current study does not include all the aspects of quality and preservation of the Step Pyramid stone material. These aspects should be further studied in detail; however, it is essential to include the data about the underground structure of the pyramid in these studies, as well as perform direct measurements and observations on the facades of the pyramid.

CONCLUSIONS

The results of the study indicate that separate facts, observations and phenomenon can yield higher value and uncover hidden correlations if this data is visualized in 3D environment. It also concerns intermediate and revisory research data raising its scientific quality by displaying this data in the high quality geospatial model integrated into GIS applications.

The surface of the stone material exposed on the facades of the pyramid has disintegrated. It was possible to evaluate not only predominant weathering types and their intensities, but also their spatial distribution and correlation with other evaluation parameters. The study results demonstrate direct connection of the material weathering to the construction stages of the Step Pyramid. Such studies along with the evaluation of the cement properties are essential before attempting any reconstruction and conservation work on the pyramid site.

Individual studies of the stone material and mortar weathering, as well as stability of the Step Pyramid substantially extend the possibilities to follow natural processes and after respective calibration to attribute appropriate quantitative evaluation. These are comparatively simple technical tools and computer software enabling wide application of such an approach in multilateral geoarchaeological studies. Moreover, this method is applicable also for extended monitoring observations of exogenic processes in different monuments and sites of cultural heritage.

The method applied in the current study is comparatively simple and easily adjustable to suite the needs of the studies of other stone monuments to evaluate their state of preservation and draw the plans for future research. The methodology developed for this study would require minor modifications in order to be applied in similar studies on the other historical stone monument sites of Saqqara and Giza plateaus.

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