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Structural Analysis of Pyramids:

Insights from the Giza 3D Survey Project

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***Abstract*—**Within the Memphis region of Egypt, the Old Kingdom period (approximately 2686–2181 BCE) saw the construction of over 70 pyramids. The extant survey data for these pyramids, derived mainly from architectural studies, have not been substantially updated. The information from this period predominantly encompasses descriptive accounts and schematic representations, focusing on the dimensions, internal chambers, and passageways of the pyramids. Notably absent are detailed documentations that provide insights into the individual stone blocks and the intricacies of their masonry. Consequently, the current understanding of the pyramid construction methodologies of this era remains largely hypothetical. Since 2005, I have been actively engaged in an interdisciplinary 3D survey initiative, focusing on acquiring laser- scanned 3D data of Memphite pyramids. This endeavor aims to analyze their structural forms to elucidate the progression in construction techniques during this epoch. Beginning in 2013, the "Giza 3D Survey" project was initiated as a collaboration between academia and industry. This project sought to comprehensively update the exterior measurement data of the Giza pyramid complex, employing "Structure from Motion/Multi-View Stereo (SfM/MVS)" technologies to generate 3D representations from photographic imagery. This comprehensive approach seeks to unravel the construction methodologies of these ancient structures. As a result of a decade-long survey, it has been discovered that the pyramids of Giza are not merely accumulations of limestone blocks. Instead, they contain a central "core structure" in a step-like formation, a framework made up of "backing stones," and areas filled with debris and sand, referred to as "chamber method."

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I. Introduction

In the Memphis region, one of Egypt's World Heritage Sites, more than 70 pyramids dating back to the Old Kingdom period (approximately 2686-2181 BCE) [1] were constructed. The oldest among them is the Step Pyramid, which served as the tomb of King Netjerikhet (also known as Djoser) and was built at Saqqara. From there, the pyramid's architectural form evolved into the distinctive square-based pyramids represented by the three great pyramids on the Giza Plateau, namely those of Kings Khufu, Khafre, and Menkaure. Surprisingly, the survey data for these pyramids have seen minimal updates since the architectural survey conducted in the 1960s [2]. The information from over half a century ago primarily consists of descriptive narratives regarding the size of the pyramids, the internal chambers, and passageways, along with schematic line drawings used for creating floor plans and elevations. Actual measured drawings indicating the size of individual stone blocks and the construction techniques employed are notably absent. Considering the lack of data, the hypotheses regarding the construction methods of the pyramids from this era remain primarily speculative. Consequently, comprehensive research on technological changes throughout history has yet to progress [3].

Since 2005, I have been involved in multinational 3D survey projects aimed at acquiring 3D data of pyramids from the Third to the Fifth Dynasties using laser scanners and photogrammetry. Through the analysis of the structures of 3D data obtained, I am conducting research on the evolution of construction techniques during the Old Kingdom period. Starting in 2013, an industry-academic collaborative project called the “Giza 3D Survey” was initiated to comprehensively update the survey data for the Giza pyramid complex's exteriors (*Fig. 1*). Utilizing Structure from Motion/Multi-View Stereo (SfM/MVS) technology, 3D data is generated from images. In 2017, with the cooperation of Amuse Oneself Inc. and Apeo Giken, we attempted to create world-standard 3D survey data by collecting image data of the Great Pyramids of Khufu, Khafre, and Menkaure using drones, conducting GNSS (Global Navigation Satellite System) surveys, analyzing this data over an extended period, and integrating it with 3D data. Since late 2021, in collaboration with the World Scan Project, efforts have been made to gain a comprehensive understanding of the construction techniques by acquiring 3D data that encompasses both the exteriors and the internal chambers and corridors of the Giza pyramid complex.

In this paper, we will focus on the 3D survey of the Giza Pyramids and provide an overview of the project.

Fig. 1. Aerial view of the Giza pyramid complex captured by a drone from the northeast.

II. 3D SURVEY OF THE PYRAMIDS

Notch and Cave of the Great Pyramid

The pyramids of the Old Kingdom are characterized by sophisticated construction techniques and are in an exceptionally well-preserved state. However, as a result, their internal structures still need to be clarified. The hypothesized internal structures include (1) horizontally stacked stones shaped similarly to the exterior, (2) an interior, staircase-like core supporting the entire structure, and (3) inward-leaning accretions where stones are stacked inclined towards the pyramid's center (*Fig. 2*) [4]. Although few exposed masonry structures are seen in the pyramids of the Fourth Dynasty, several areas in the Giza pyramid complex indicate such construction. These include a recess on the northern entrance, a notch at the northeast corner, and the top of Khufu's pyramid, the top of Khafre's pyramid and the great gash (massive depression) on the north face of Menkaure's pyramid [5].

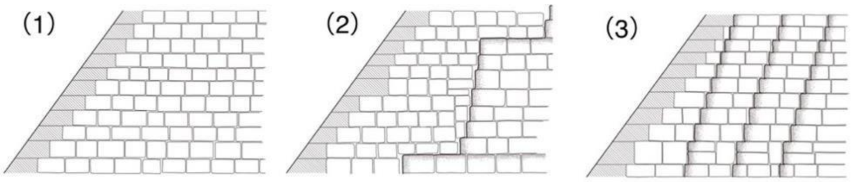

Fig. 2. Proposed internal masonry structure of the pyramid (After Arnold, D.)

In 2013 and 2015, investigations were conducted on the "notch" and the "cave" located at the northeast corner, 80 meters from the base of the Great Pyramid. The notch is situated at the 104th course of the pyramid, and at the southwest corner of this notch, a fissure leading to a small cavity-like space was discovered. These structures were filmed under the permission of the Supreme

Council of Antiquities (now the Ministry of Tourism and Antiquities) of Egypt by the author and a television crew. The acquired images and video data contributed to creating elevation images of the masonry structure through a collaborative research project using SfM/MVS to complete a 3D model [6].

While 3D data enables an intuitive understanding of the surface structure of objects, two-dimensional plans and elevations are typically used to grasp the shape features of archaeological structures. Therefore, the unique display method PEAKIT, developed by Lang, was applied [7].

As a result, the dimensions of the cave were found to be 3.3m in the north-northeast to south-southwest direction and 2.9m in the west-northwest to east-southeast direction. While the outer casing stones of the pyramid are aligned along the cardinal directions, the internal "cavity" exhibited irregularities at each course. Furthermore, the height of the external three courses (106th, 107th, and 108th courses), which measures 2m, did not match the 2.3m height formed by the three internal courses [8].

When examining the structure of the notch and the cave of the Great Pyramid, it becomes evident that they differ from any of the previously hypothesized stone construction methods (*Fig. 3*). As will be shown later, the interior of the pyramid contains a stair-like structure, but it is also believed that "chamber systems" like the one described may be present in certain locations. This could potentially account for the variety of densities identified by precision gravimetric measurements in the 1980s [9].

Fig. 3. PEAKIT elevation diagram of the notch and the cave

A. The top of the Great Pyramid

In Egypt, where Arabic is the official language, drones are referred to as "spy planes." Due to their potential military use, the importation of drones into the country and their use at archaeological sites are strictly regulated. For this study, special permission was obtained from Egypt's National Security Agency, and cooperation from an authorized company was secured to conduct aerial photography of the pyramid's top (*Fig. 4*).

The top of the pyramid was photographed using an aerial drone (static image 4000x2250 pixels, ISO100, 1/1250 second, f2.8), and the images were converted into 3D using photogrammetry software. I then projected nine lines, measured at the top of the pyramid with a convex tool, onto the 3D data to assign distances [10].

- Number of images used: 92 drone photographs, with all 92 images utilized.
- Software: Agisoft PhotoScan Professional Version 1.3.1.
- Number of generated point clouds: 2,494,377.
- Number of generated surfaces: 4,974,384.
- Error during coordinate assignment: 0.090095 meters.

Fig. 4. Top of the Great Pyramid, captured by a drone from the northwest

The top of the Great Pyramid, above the 202nd layer, is missing, allowing for the observation of the masonry construction on a flat plane (in reality, only 18 stones of the 202nd layer remain, so what is exposed is the 86 stones of the 201st layer). Most of the high-quality casing stones that once covered the pyramid's exterior are now lost, and what is exposed are the "backing stones" placed between the casing stones and the core interior. These are thought to have served as a support for the casing stones, but their exact function remains unclear.

To confirm whether the 201st layer's exterior was composed of backing stones and to determine the extent of the lost casing stones, the method of geometric similarity was employed, using the length of one side of the pyramid's top (*Fig. 5*). Assuming that the “mini-pyramid” from the original top to the 201st layer and the original pyramid from the original top to the ground are similar, the figures share the same proportions when comparing the lengths of their respective sides. Therefore, knowing a part can reveal the whole. The average length of the original pyramid's base (a) is 230.329 meters, the original height (d) is 146.58 meters, and the current height (d) is the total of all steps measured by the author while climbing the Great Pyramid in 2015, resulting in a mini-pyramid height of 8.7 meters (e) [11]:

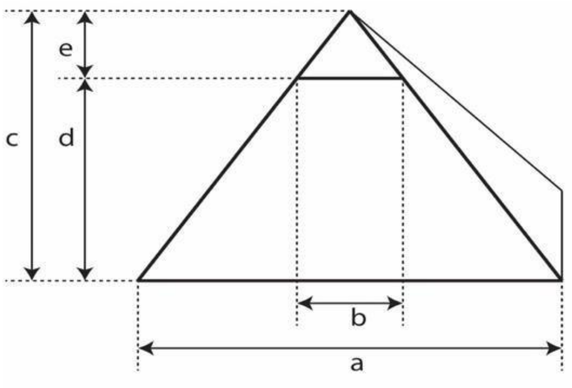

Fig. 5. Diagram illustrating the original dimensions of the lost apex of the Great Pyramid, shown in 'similarity'

- Original base length (a): 230.3 meters
- Mini-pyramid base length (b): ?
- Original height (c): 146.6 meters
- Current height (d): 137.9 meters
- Mini-pyramid height (e): 8.7 meters
- Formula: b/a = e/c
- Where c = d + e
- Therefore, b = a(e/c) = a(c-d)/c = 13.64 meters

As a result, the original length of the 201st layer was 13.64 meters. Considering the current lengths are north-south 11.7 meters and east-west 11.9 meters, approximately one stone's width has been lost, revealing that the existing exterior stones are indeed backing stones. Furthermore, cross-sectional 3D data of the top part, generated along each row north-south and east-west, showed that while the internal masonry had irregularities, the external backing stones maintained almost perfect horizontality [12] (*Fig. 6*).

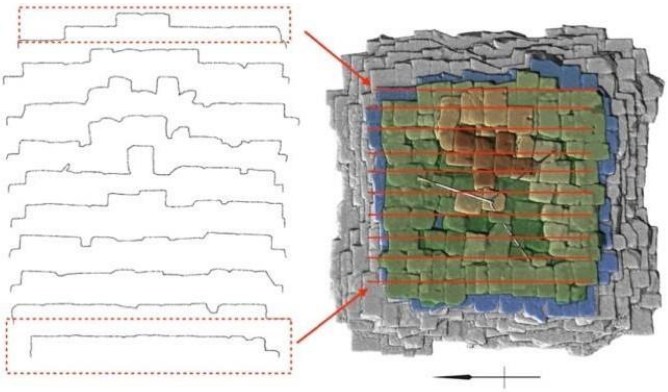

Fig. 6. PEAKIT plan and cross-sectional views of the top of the Great Pyramid

B. The Great Gash of in the Pyramid of Menkaure

Although the Pyramid of Menkaure in Giza has not received as much attention as the other two great pyramids, the great gash (large depression) on the north face represents the most significant area, revealing the pyramid's masonry structure. (*Fig. 7*).

Fig. 7. The Great Gash in the Pyramid of Menkaure

The first record of this depression dates back to the 12th century [13]. According to "The Chronicles of Egypt" by Abd al- Latif al-Baghdadi, in 1196, when Malik al-Aziz Othman bin Yusuf succeeded his father, he was persuaded by ill-advised courtiers to demolish the Pyramid of Menkaure. Civil engineers, miners, and workers were dispatched, and for eight months, only a part of one side of the pyramid was dismantled. This is believed to be the origin of the great gash on the north face. The next to explore this site was Howard Vyse, a British military officer known for his "dynamite excavations." In 1840, he dug a 15m horizontal tunnel from the great gash into the interior of the pyramid and then continued downwards vertically [14]. The architectural study of this site was conducted by Italians Vito Maragioglio and Celeste Rinaldi, whose records and interpretations remain the primary sources of information about the great gash [8].

Our team acquired images of this site with a drone from 2016 to 2018 and integrated these with GNSS data to create 3D data (*Fig. 8*).

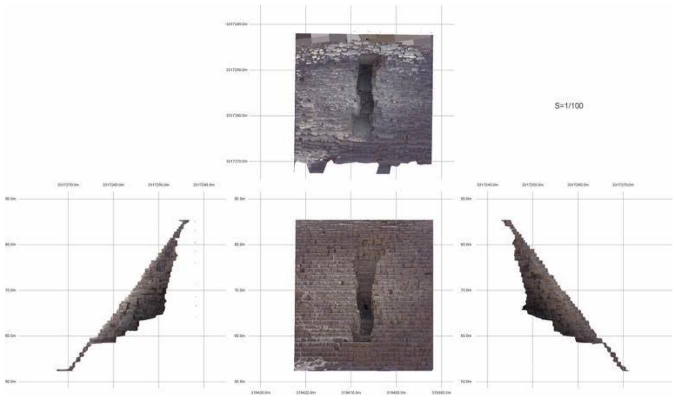

Fig. 8. The plan and sections of the great gash

- Number of images used: 5140 drone photographs were taken, of which 2806 images were used.
- Software: Agisoft PhotoScan Professional Version 1.5.1.
- Number of generated point clouds: 272,593,677.
- RMS error: 0.04m.

The great gash is a massive crevice on the pyramid's north face, spanning from the 15th (upper) to the 44th (lower) step, approximately 22.4m high and 2.5 to 5.7m wide. Maragioglio and Rinaldi stated, "The pyramid's core is made of large steps. Of these, the inner or outer edges of what are believed to be the second, third, and fourth steps can be identified. There were probably two more steps above this." However, the 3D-generated cross-sectional view shows the third and fourth steps, but not the second [15].

The 3rd step appears to originally consist of seven layers of stones, but currently, only the second and third layers from the bottom exist, with parts of the fourth and fifth layers remaining on the west side. The heights of each layer are approximately 1.27m, 1.19m, 1.19m, and 1.22m from top to bottom, slightly receding in form, resulting in an angle of 75.3 degrees (75°18'00").

The fourth step comprises seven neatly flattened layers, distinct from the roughly surfaced stones outside. Interestingly, the heights of these seven layers do not match those of the backing stones of the currently exposed casing stones. The heights of each course are 1.07m, 1.27m, 1.16m, 1.27m, 1.29m, 1.13m, and 1.21m from top to bottom, with the total height of the fourth step being about 8.4m. These layers also slightly recede, forming an angle of 75.3 degrees (75°18'00"), different from the 81.4 degrees shown in Maragioglio and Rinaldi's cross-section [16].

This 75.3° (75°18'00") angle in the core structure aligns closely with the exposed core structures of the collapsing pyramid of Sneferu at Meidum and the Step Pyramid of Djoser, the oldest pyramid. This angle, which could be termed the "Netjerikhet angle," not only represents architectural stability but also aligns with ancient Egyptian construction customs. Tomb construction was part of a larger ceremonial cycle, and covering old styles with new in ancient Egypt was an act of integration and regeneration [17].

III. CONCLUSION

The documentation of ancient structures is significantly transitioning from traditional manual two-dimensional drawings to three-dimensional records. The acquisition of 3D data, initially based on laser measurements that include geographic information, is becoming increasingly widespread due to the affordability and convenience of photogrammetry software and drone imagery. However, integrating this data with geodetic systems through georeferenced laser measurement data or GNSS data is essential. This integration transforms the data from mere shape information into academically usable data. In the context of ancient Egyptian pyramids, this approach can elucidate the structure's masonry, the function of exposed backing stones, and their relationship with casing stones.

The challenge ahead lies in the methods of data dissemination. While there are known platforms for the online publication of 3D data and open-source repositories for large datasets, their general use is not yet widespread. There is an anticipation for the emergence of more user-friendly and accessible platforms in the future.

These advancements in 3D documentation techniques offer significant benefits for archaeology and Egyptology. By accurately capturing and preserving the current state of ancient structures in 3D, researchers can conduct more detailed analyses without the physical constraints and potential risks associated with on-site investigations. Moreover, this technology facilitates sharing detailed structural information with a global audience, including researchers who may need the means to visit the sites in person.

The integration of 3D data with precise geographic coordinates also enhances the academic value of the findings. It allows for precise comparisons with past records and other structures and assists in the study of architectural development over time. With the evolving technology and platforms, it is expected that the accessibility and utility of 3D data in ancient structure studies will continue to improve, providing invaluable tools for researchers and enthusiasts alike.

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