Basic considerations on the construction of pyramids in the Old Kingdom

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Abstract

Given that the lower third of a pyramid contains about 70% of the stone blocks, the only efficient way of reducing building time at the minimum is a method which allows for upward transport of material from all four sides simultaneously. Ramps positioned tangentially with a slope of 26° come to mind. The time required for upward transport of blocks significantly influences the total building time. By comparison, the production of blocks in the quarry as well as their transport to the building site and horizontal transfer on the respective level would have been far less challenging as more workforce would have been available. In the model presented here, upward pulling of blocks on horizontal rollers is accomplished by letting workers move downwards on the other side of the ramp. After completion of the stepped core, the ramps are removed, and the casing, which consists of horizontal courses, is laid. For this, a stepped auxiliary platform and tangential ramps are used. Thus, it is possible to set the pyramidion and subsequently polish the exterior face top down without significant danger, while also removing the auxiliary platform.

Keywords

Pyramid building; steep tangential ramps; pyramidion; Pyramid of Menkaure

Introduction

Over the years there have been many hypotheses concerning the construction of the pyramids in ancient Egypt – amongst others from well-known Egyptologists. In this paper some basic considerations and conclusions will be introduced and the hypotheses will be discussed that have so far been brought forward. Based on this, a solution will be presented for the problem of the construction of the pyramids in the Old Kingdom.

Life expectancy in ancient Egypt was on average 35 years. Despite the relatively high standard of medical care many inflammations, especially as a result of injury, were fatal. Even in living conditions with above-average hygienic standards, excellent medical care and a good diet, kings and high-ranking officials were still affected by suddenly occurring fatal illnesses.

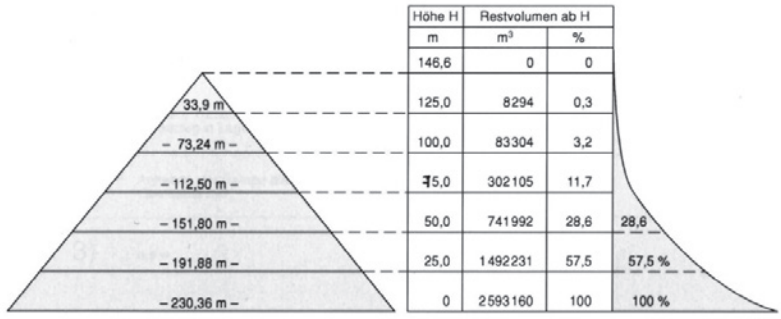

FIGURE 1: IN THE LOWER THIRD OF A PYRAMID, 71.4% OF STONES ARE USED. THIS CAN BE ILLUSTRATED WITH THE HELP OF THE PYRAMID OF KHUFU: AT A HEIGHT OF 50M, THE REMAINING VOLUME OF MASONRY IS JUST 30% (© FRANK MÜLLER-RÖMER).

Of 22 kings of the 3rd to the 6th Dynasties who built pyramids, at least six died before the completion of their tombs: Sekhemkhet, Khaba (Maragioglio and Rinaldi 1963–1970, II: 20, 31ff), Djedefre (Stadelmann 1997: 128), Bikheris (Maragioglio and Rinaldi 1963–1970, VI: 16–26), Shepseskare (Verner 1982: 75–8) and Neferefre (Stadelmann 1997: 174).

It can thus be assumed that upon accession every king arranged for his pyramid to be planned, built and completed as soon as possible. Therefore, as short a construction time as possible determined the construction method used. This was the highest priority for the construction of the pyramid.

Basic considerations and preliminary conclusions

In the lower third of a pyramid, 71.4% of stones are used. This can be illustrated with the help of the pyramid of Khufu: at a height of 50m, the remaining volume of masonry is just 30% (Figure 1).

Transport of material using only **one** ramp always leads to a higher expenditure of time than a means of transport using several ramps simultaneously. Besides, many construction sites did not have room for such long ramps leading to the pyramid at a right angle.

– This leads to **conclusion no. 1**: A relatively short construction time is only possible by simultaneously building at all four sides of the pyramid (Figure 2). The number of ramps that are tangentially attached to the pyramid determines the construction time.

Extensive storage of stones at the construction site was not possible due to space constraints. For the Old Kingdom there is no archaeological evidence for lifting devices. Therefore stacking stones as a form of storage was out of the question.

– This leads to **conclusion no. 2:** The manufacture of the stones, transport of the materials to the construction site, and the construction of the pyramid itself had to be carefully coordinated at all times. Today, we refer to such a system whereby every step is precisely coordinated as ***just in time manufacturing***. But this is by no means an invention of our time. This method was already employed in the construction of the pyramids of the Old Kingdom.

The time needed for the transport of the stones via steep tangential ramps to the current construction level was thus the determining factor with regard to construction time.

The amount of stones needed on a day-to-day basis could be manufactured in several quarries simultaneously.

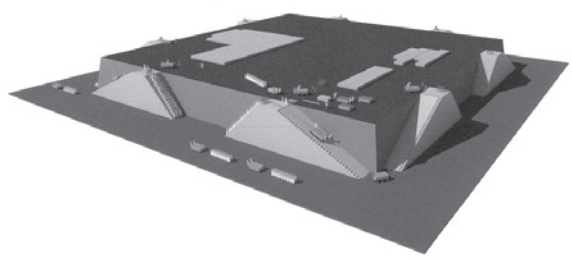

FIGURE 2: A RELATIVELY SHORT CONSTRUCTION TIME IS ONLY POSSIBLE BY SIMULTANEOUSLY BUILDING AT ALL FOUR SIDES OF THE PYRAMID (© FRANK MÜLLER-RÖMER).

Archaeological evidence indicates that this kind of approach was used in the construction of the Pyramid of Khufu (Lehner 2004: 32ff) and the Red Pyramid (Arnold 1991: 82).

Similarly, transport from the quarries to the construction site could take place simultaneously via several transport ramps, as in the case of the Red Pyramid and the Pyramid of Khufu.

The horizontal positioning and placing of the stones on the respective upper level of the unfinished pyramid could be carried out by a large number of workmen at the same time (Figure 2). Both work phases were only dependent on the amount of stones transported via the ramps and therefore not essential/crucial for construction time.

- **Conclusion no. 3:** The transport ramps from the quarries to the construction site only had a maximum slope of 7–8°, as proven by archaeological findings (Müller-Römer 2011: 81). This prevented a sliding back of the stones during necessary breaks taken by the hauling crews or teams of oxen (Müller-Römer 2011: 80). Static friction always had to be higher than the downhill-slope force.
- **Conclusion no. 4:** The tangential ramps on all four sides of the pyramid, however, could be significantly steeper due to the shorter hauling distances. Hauling breaks were not necessary (Figure 3).

The building technique of the Pyramid of Djoser – and that of Sekhemkhet, Khaba, and those of Snofru at Meidum and Dahshur South (Bent Pyramid) – is known in the modern literature as 'layer pyramids': several accretion layers leaning inward form the substructure of the pyramid (Müller-Römer 2011: 143ff).

As a consequence of heavy earthquakes over the last 4000 years in Egypt, the pyramid at Meidum, the Bent Pyramid at South Dahshur and the Red Pyramid at North Dahshur, among others, suffered major structural damage. A high pressure on the underlying soil layer, which was not always stable, contributed to this damage. The weight of these pyramids per m² is far higher than that of modern high-rise buildings.

The builders of Snofru, therefore, with a view to future earthquakes, decided to lay the stones horizontally in the upper part of the Bent Pyramid, the construction of the subsidiary pyramid to the Bent Pyramid, as well as the Red Pyramid. Furthermore, the latter was built with a reduction of the recess to 28 fingers per cubit, i.e. at an angle of 45°.

There was a further change in the construction of the Pyramid of Khufu, for which, as a construction site, the very solid Nummulite limestone plateau near Giza was chosen. In addition, the pyramid was probably built with a substructure made of steps which was cased after completion. These are results of examinations and measurements made by the author at the Pyramid of Khufu.

This substructure, consisting of steps, is clearly visible in the great gash of the Pyramid of Menkaure, which is up to 8m deep and was cut open by the Mamelukes while searching for the entrance.

The core of the pyramid, therefore, is made up of rectangular stone structures, similar to *mastabas*, getting smaller going up. The outer walls are slightly leaning inwards and are made of carefully worked stones; the inside is filled with stones of different sizes, the spaces in between these stones are filled with sand and *tafla* for an even distribution of pressure. An advantage of this building technique is that seismic shocks can be better absorbed than when inflexible masonry is used.

The second, third and fourth steps are clearly visible in a section of the northern side drawn by Maragioglio und Rinaldi (Maragioglio and Rinaldi 1963–1970, VI: 34, 94ff, Addenda, TAV. 4, fig. 2, cutaway diagram S–N) and pictures by Frank Müller-Römer (Figure 4).

A substructure consisting of steps is also clearly visible in the Queens' pyramids of Khufu and Menkaure.

The construction of this kind of substructure, and the casing of the pyramids, was consistent until the end of the 6th Dynasty, as is evident in the archaeological record (Maragioglio and Rinaldi 1963–1970, VII: 12, 46, 116, 176; VIII: 10ff, 66; Verner 1997: 71–6; Tietze 1999: 59; Müller-Römer 2011: 196ff, 210).

- **Conclusion no. 5** is therefore: From the construction of the Pyramid of Khufu onward, the pyramids of

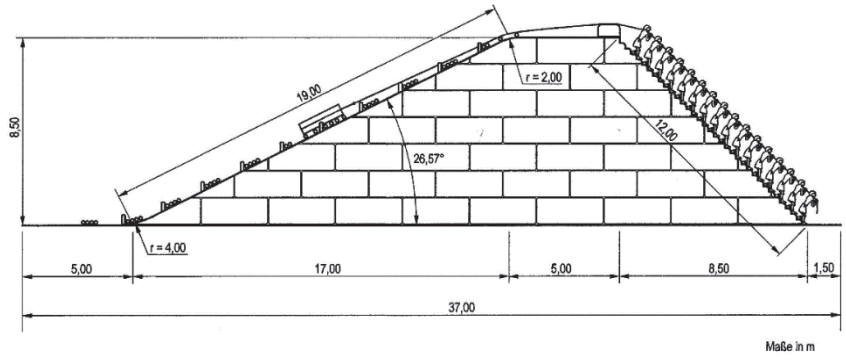

FIGURE 3: TANGENTIAL RAMPS ON ALL FOUR SIDES OF THE PYRAMID COULD BE SIGNIFICANTLY STEEPER DUE TO THE SHORTER HAULING DISTANCES (© FRANK MÜLLER-RÖMER).

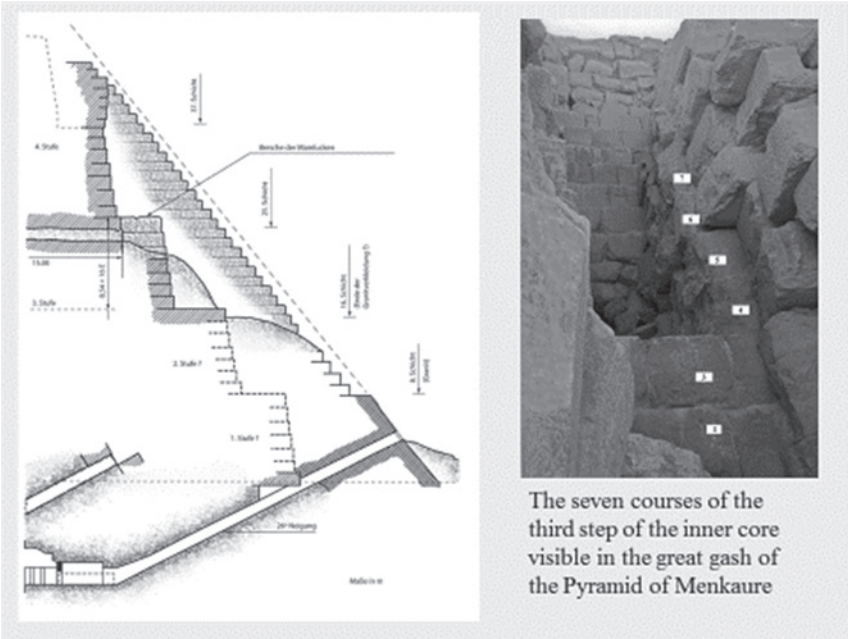

FIGURE 4: THE SEVEN COURSES OF THE THIRD STEP OF THE INNER CORE VISIBLE IN THE GREAT GASH OF THE PYRAMID OF MENKAURE (© FRANK MÜLLER-RÖMER).

the 4th to the 6th Dynasty are clearly built as step pyramids.

– A further **conclusion (no. 6)** is as follows: From an engineering point of view, the construction of the casing of the pyramid, the placing of the pyramidion, and the subsequent smoothing of the casing from top to bottom, could only be executed by using scaffolding or platforms that were not attached to the casing. The workmen needed stable and safe platforms to execute these tasks.
– The 7th and final **conclusion** says that the hypotheses on the construction of pyramids during the Old Kingdom can only include tools and devices, as well as methods for procuring materials and means of transport, for which there is archaeological evidence. These are chisels made of copper, dolerite pounders, wooden beams used as levers, transport slides, sloping levels and ramps, roller and deflection pulleys, ropes, measuring sticks, angle gauges, and sculptors cords.

With these seven conclusions derived from the requirements of construction, the archaeological record and the time constraints, the essential prerequisites for the construction of the pyramids are defined.

Construction of pyramids using steep tangential ramps and auxiliary construction

The individual construction phases will be illustrated here using the example of the Pyramid of Menkaure.

After the completion of the base, the core masonry of the Pyramid of Menkaure was constructed with six steps. Using tangential ramps, the building materials could be transported upwards on all four sides simultaneously. After completion of the core masonry the ramps were built back (Figure 5).

There is much archaeological evidence from the Old Kingdom for steep ramps with an inclination of 1 (height) to 2 (base), corresponding to an angle of 26.5°, for example at entrances to burial chambers as well as in illustrations in private tombs (Maragioglio and Rinaldi 1963–1970, VI: Addenda, TAV 6, fig. 1; Davies 1948). Thus, this angle is supposed to be the state-of-the-art at the time of the suggested tangential ramps.

The question, whether the core was constructed separately or whether construction phases 1 and 2 were carried out simultaneously, is still open. Results from examinations made by the author on-site suggest that the casing on the Pyramid of Menkaure was added to the steps of the core masonry with stones of different height. This supports a construction in two separate phases, with additional expenditure for the deconstruction of the ramps (Figure 6).

After completion of the core masonry its ramps are dismantled. Afterwards the casing is added. This is surrounded by a stepped auxiliary construction with additional ramps. The auxiliary constructions are supported against protruding stones of the not yet smoothed casing. In this way, the pyramidion can be safely transported via the ramps to the topmost platform and then moved onto the top of the casing horizontally (Figure 7).

During the subsequent third construction phase, the ramps are dismantled from top to bottom. At the same time the casing is smoothed thus minimizing the risk for the workmen who are assigned to this task.

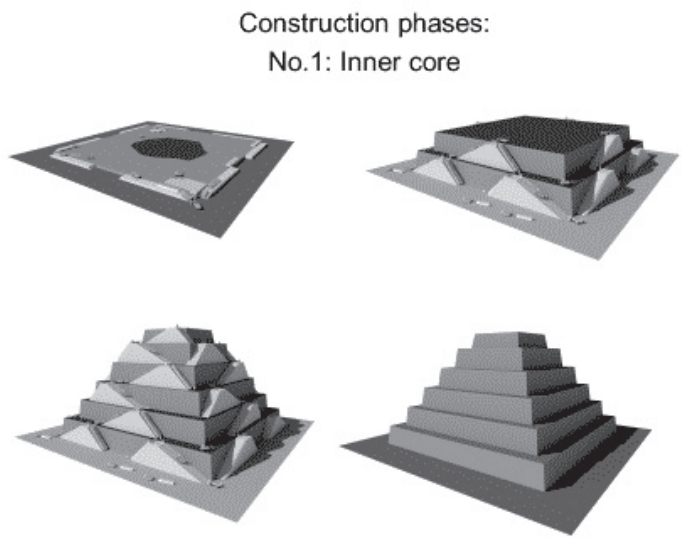

FIGURE 5: CONSTRUCTION PHASE 1 – THE INNER CORE (© FRANK MÜLLER-RÖMER).

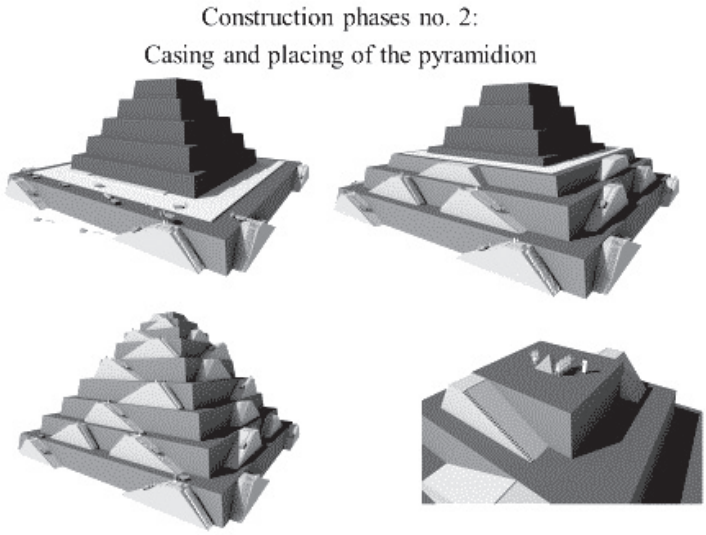

FIGURE 6: CONSTRUCTION PHASE 2 – CASING AND PLACING OF THE PYRAMIDION (© FRANK MÜLLER-RÖMER).

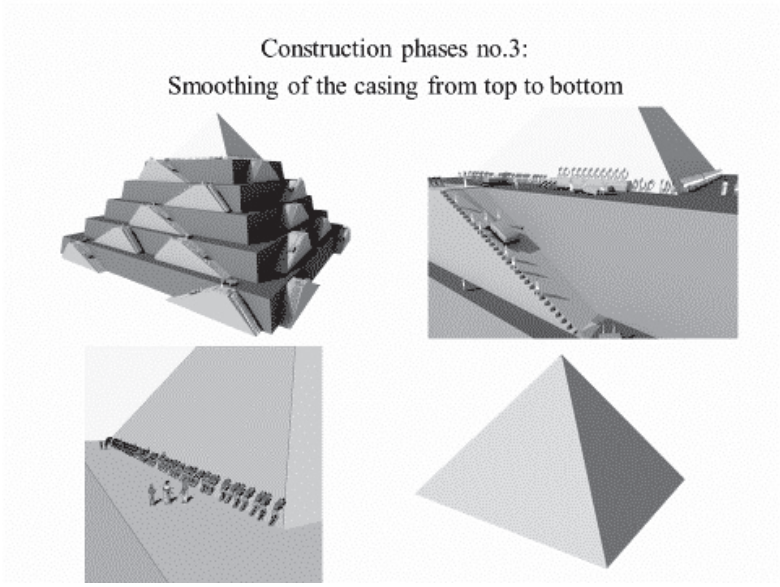

FIGURE 7: CONSTRUCTION PHASE 3 – SMOOTHING OF THE CASING FROM TOP TO BOTTOM (© FRANK MÜLLER-RÖMER).

The following assumptions are made: average size of stones 1.2m³ (weight = 3 tons) and weight per hauling process 3.2 tons. Cycle time for one hauling process via the ramps (Figure 2) is estimated at 15 minutes, with 10 hours working daily, in shifts, on 300 days a year. Unfortunately, the cycle time of 15 minutes, which was settled on after discussing the issue with construction engineers, could not yet be verified. However, the actual construction time of the pyramid is heavily determined by this. A proposal for an experimental trial in 2014 was submitted to the German Research Foundation (DFG), but, sadly, rejected.

Construction time for the core masonry, the casing and its smoothing, the construction and dismantling of the ramps, as well as the preparatory works for the Pyramid of Menkaure, according to this method, amounts to approximately 4.8 years.

A comparative calculation for the Pyramid of Khufu and the Red Pyramid adds up to construction times of 22.5 and 18.7 years respectively. In doing so, construction for the Red Pyramid is assumed to have started in the 15th year of Snofru's livestock census (Gundacker 2005: 9–23).

The construction times calculated for the three pyramids are thus consistent with the length of the reigns of these kings: Snofru 35 years 9 (Krauss 1977: 1ff; 1996: 43ff), Khufu 23 years, and Menkaure – most recently found to have been 6 years (Hornung, Krauss, and Warburton 2006: 491).

Concluding remarks

The suggestion that pyramids in the Old Kingdom were built using steep tangential ramps and auxiliary constructions was first published by the author in 2008, and since then has been presented and discussed in various publications. Up until now, no scientifically substantiated contradiction has been published.

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