How the Great Pyramid of Giza was built. An Engineering View.

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ABSTRACT

Today, more than forty centuries after the Pyramids at Giza were completed, the fact of how they were constructed remains a mystery. Although several hypotheses have been advanced, this pyramid has successfully kept the secret throughout the millennia. For more than 4500 years the height of the Great Pyramid of Khufu (Cheops) was the benchmark for tall building achievements. The present study investigates on these points in a more viable manner than the theories hitherto advanced. To obtain a more accurate perception of how the pyramids were built, we concentrated our efforts on exploring certain insufficiently explained factors in the existing theories on the construction of the Great Pyramid. Investigating these hypotheses from the engineering point of view, we notice that they have several untenable facts in their present forms. Utilizing the results of our study, we would advance the basis for a new theory that may satisfy the required conditions.

Keywords: *pyramids of Giza, hypotheses, untenable facts.*

1. INTRODUCTION

The Great Pyramid, part of the 4th Dynasty at Giza, was built across the Nile river, Cairo. The time of its construction is considered 20 years, about 2550-2530 B.C. Some general dimensions of the Great Pyramid are listed below:

- side of the square base 230.36 m
- height (original) 146.7 m
- height (today) 137 m
- $height = \frac{perimeter}{2 \cdot \pi} = \frac{4 \cdot 230.36}{2 \cdot \pi} = 146.7m$
- volume 2. 595. 000 m^3
- weight 6. 550. 000 tons
- slope of walls 51º52'
- approximate number of stones 2. 300. 000

There are used two different types of stone as material for the pyramid:

- local yellowish limestone for the core
- Fine white Turah limestone for the surface casing with estimated thickness of three meters.

This pyramid has some specific properties that make it different from most other solids construction. In particular, the sharp decrease of the horizontal section from the base to the vertex, which makes that the volume of the pyramid notedly changes with the increase of the height. The volume of the first 10 m of height is 19% of the total. At 100 m the volume reaches 96.8% of the total and for the remaining 46.7 m the volume is only 3.2%; 50% of the pyramid volume corresponds to 1/5 of its height because the center of gravity is located at 30.25 m from the base. The entrance to the pyramid is in the centre of the northern face and is located in the 13th course of masonry from the base. This entrance has a pointed roof and opens into a long steeply descending passage. From there, a 36 meters long ascending passage leads to a 35 meters long horizontal passage that leads to the Queen's chamber. This chamber measures 5.2×5.7 meters with maximum height of the pointed roof about 15 meters. From the horizontal passage, starts the Grand Gallery which leads to the King's chamber. It measures 47 meters long and 8.5 meters high, with a corbelled roof. In the centre of the floor is a sunken ramp about 60 centimeters deep. The Grand Gallery ends in a horizontal passage made from granite, which serves as an antechamber. It measures 8.4 meters long and 3.1 meters high. Beyond the antechamber is the 'King's Chamber' which is lined, roofed and paved with red granite. It measures 5.2×10.8 meters and is 5.8 meters high. Its flat roof is formed of nine monolithic slabs of granite. The northern and southern walls each have an "air channel", one of which is open to the outside. There were approximately 209 layers to the Great Pyramid. The layers all have a different thickness ranging between approximately 50 and 145 centimeters. Based on these estimates, building this in 20 years would mean installing approximately 800 tones of stone every day. Similarly, would involve moving an average of more than 12 of the blocks into place each hour. One of the major problems faced by the early pyramid builders was the need to move huge quantities of rock. In the below we will examine some hypotheses about this and try to determine the most correct one.

Methods of lifting the blocks up the Egyptian pyramids have attracted a considerable amount of research. There is a lot of information about the location of the quarries, tools used to split and shape the stone, transportation of the stone from the quarries to the pyramid, methods of leveling the foundation and rising pyramid tiers, but there is a lack of information connected to the methods of moving the blocks up the structure. There are no direct historical or archaeological conclusions available to resolve this aspect of construction. Without strong conclusions from archaeological or historical sources, we must select methods of moving blocks up the pyramid structure that are technologically and historically possible. In other words, we must identify models that have the best historical and archaeological information; and then intersect this information with materials, culture and technology.

2. RESEARCH METHOD

The method engaged in this study has in focus different hypothesis suggested by many authors related to this subject. This research method used in this paper is called secondary data collection, which consist in existed data collected from literature review conducted all over the world.

These hypotheses were analyzed and results and conclusions were maid related to each of them.

3. RESULTS AND DISCUSSION

The models with the best historical, archaeological, material, and technological connections are ramps. The materials to construct these ramps are easily found within the pyramid structure. The evidence for ramps is strong, arguments of functionality exclude ramps as a solution to this aspect of pyramid construction.

The 4th dynasty Giza pyramids seem to serve as the standard testing ground of pyramid construction hypotheses. The logic behind this seems to lay with the total volume of this particular pyramid, also its large block sizes. To test a sweeping method by the standards of the Great Pyramid is to test the technique against variables that add blocks with the largest mass and volume. There is a considerable amount of discrepancy regarding what type of ramp was used to build the pyramids. The archaeological data gives evidence of only small ramps, not something that could have been used to construct even a majority of the construction.

These factors in combination with the variable distance and location of the quarries in relation to the pyramids have lent themselves to an array of ramp hypotheses, that can be classified into *straight* ramps, *spiraling* ramps, and *zigzagging* ramps.

3.1. Straight, Large Ramp

The earliest and most generally rejected ramp is the large, straight ramp. The construction of this kind of ramp would have been an enormous construction project on its own. The ramp needed to be modified each time for more height (would have to be lengthened and extended on the sides to support the weight). The large straight ramp presents other problems as well. A straight-on ramp with a ten to one incline would extend past the quarry site. The construction material used on such a ramp would present its own limitations.

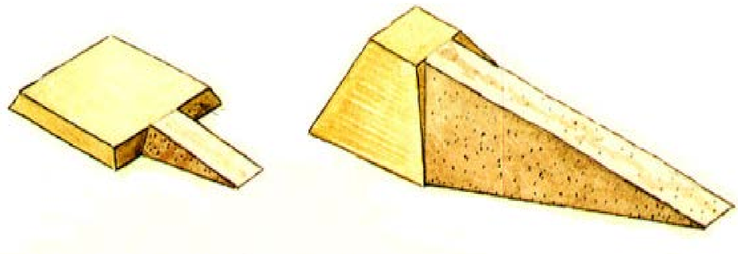

Fig.1 single, large, straight ramp

The ramp would have to be very wide because sand has a more acute angle of repose, than that of the pyramid. Large ramps require a volume of stones almost equal to that used in the pyramid itself. In addition, the work would have to be interrupted continually every time the ramp should be extended. Such ramps would be either short while too steep to be useful, or shallow but several kilometers long. It seems irrational to build the entire pyramid with a large frontal ramp.

3.2. Straight, Zigzagging Ramps

One of the alternate hypotheses to the large, straight ramp method has the ramp moving up on one face of the pyramid in a zigzag motion from one corner to the other. While the ramp reduces the construction material problem presented in the large straight ramp, it shares some of its flaws. Such a ramp would be unable to complete the entire structure.

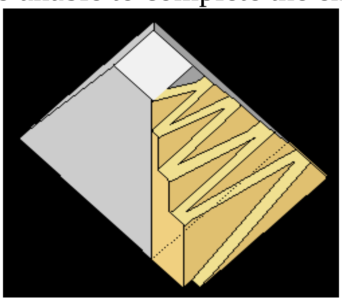

Fig.2 straight, zigzag ramp

With every increase in height, the entire ramp needs to be changed to meet the new elevation. Since one entire side is enveloped by a large ramp accretion, not all four corners are accessible for back sighting. If the angles of the zigzagging ramp remain the same, then the decreasing horizontal space offered by the face the pyramid reduce the upward distance of the ramp. To make such a model work would require ramps of increasing angles of ascent and staircase ramps at the top of the pyramid.

3.3. Straight Ramp Utilizing Part of the Incomplete Structure

Is a method very similar to the large straight ramp, which utilizes part of the growing structure as part of the ramp itself. This mean that the straight ramp cuts into the structure and continues through the interior of the pyramid. But, there are some flaws in this theory. The large amount of material left uncompleted trenches in the superstructure.

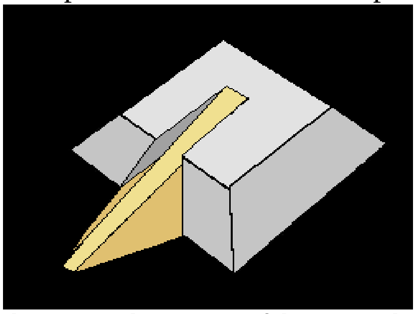

Fig.3 straight ramp utilizing part of the incomplete structure

These trenches would have disturbed the proper building of the pyramid interior. This model is an incomplete technique due to its inability to complete the structure. There would be only a minor amount of material left unreachable with this method and the remainder could be constructed with exterior ramps.

3.4. Spiraling Ramps Fully Supported by the Structure

The spiraling ramp hypotheses was arised out of a need to address the problems found in the large, straight ramp method, a ramp that spirals up at a 10% grade around the entire structure. It can be constructed with less material than the large straight ramp.

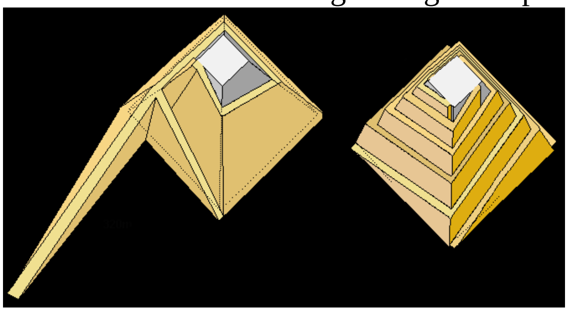

Fig.4 spiraling ramp fully supported by the structure

It would leave corners visible to backsight and would allow control over the slope of the pyramid. However, there are problems with this technique. This ramp is also unable to complete the critical top portion of the pyramid. It runs out of space at the top for reasons of converging pyramid faces and overlapping ramps. Spiraling ramp works under the supposition that the ramps would sit on unfinished casing stones, which would resemble steps. Ramps of this nature require a stepped surface to allow the spiraling ramp to cling to the surface.

3.5. Spiraling Ramp Leaning on the Pyramid as a Large Accretion

Is another spiraling ramp technique serves to solve the problems of lack of a stepped surface for support. This ramp design would lean upon the pyramid superstructure as a large accretion.

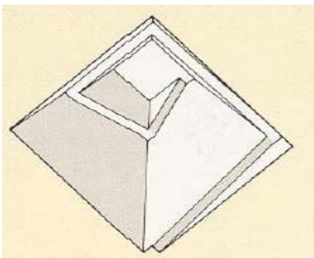

Fig.5 spiraling ramp leaning on the pyramid as a large accretion

This accretion does not require the pyramid surface to be stepped, instead only requiring some of the casing blocks to provide support. One of the more glaring issues criticizing this technique is the often repeated issue of the ramp cloaking the pyramid face, making the growing structure unavailable for backsighting.

3.6. Jean-Pierre Houdini's internal ramp theory

Jean-Pierre Houdini had his own theory of how the Great Pyramid of Giza had been built. He explained why some blocks in the Pyramid were limestone and others granite; why the patterns of stone in some walls were different from others. He even had topographical maps of the Giza Plateau to show how the architects of the Great Pyramid took advantage of the natural contours of the land to move huge blocks of stone. Jean-Pierre explained the difficulties with the two competing theories of how the blocks in the Pyramid were raised to the top. The single ramp theory could be easily discredited. As the Pyramid grew, the ramp was raised and extended. The problem is that to keep the slope gentle enough so men could haul blocks, the ramp would have to be several km long. Building just the ramp would have taken thousands of men decades. Also, there would have been a tremendous amount of debris

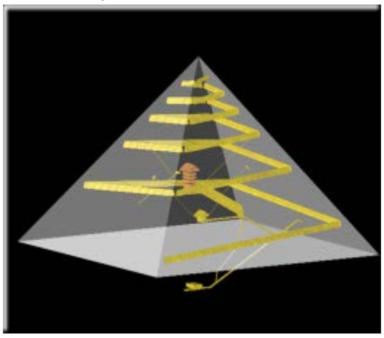

Fig.6 internal ramp

from such a ramp, but huge piles of rubble have never been found. Perhaps most damaging to the single ramp theory is the fact that there is practically no place to put such a long ramp on the Giza Plateau. The second theory fared no better in Jean-Pierre's analysis. It posited that a ramp had corkscrewed around the outside of the Pyramid itself, like a road winding around a mountain. This solves the no-space problem. But this theory has a fatal flaw as well. The Pyramid has four corners, and as the Pyramid grew, the architects had to constantly sight along those corners to make sure the edges were straight and thus ensure that they would meet at a perfect point at the top. But a ramp corkscrewing up the outside would have obscured these sight lines. Thus this too couldn't be how the ancient Egyptians raised the blocks to the top [14].

Jean-Pierre show graphics of what the Pyramid looked like, year by year, as it was being built. And then he sprang his theory. He claimed that *inside* the Great Pyramid was a mile-long ramp corkscrewing up to the top, which had remained undetected for 4,500 years! There are three chambers inside the Great Pyramid, and Jean-Pierre gave us the construction details of all three, but the great puzzle is the mysterious Grand Gallery. It doesn't make any architectural sense. It is a long hallway sloping upward inside the Pyramid, leading to the King's Chamber. But why the twenty-eight foot ceiling? And why line the side walls with low stone benches with strange grooves carved in them? But this theory had an answer for every question. Perhaps the function of the Grand Gallery is connected in some way to the next major construction, the King's Chamber. Is there some aspect of the King's Chamber that is unique and would have led to the construction of something like the Grand Gallery? At first glance, the answer was "no." But when he looked again at the details of the King's Chamber, the answer was "yes." Forty-three huge granite beams ranging from thirty to more than sixty tons each were used to build the King's Chamber. They had to be raised more than 140 feet onto the Pyramid, and nothing like that had ever been done in Egypt.

A small open notch on the outer façade of the pyramid, about 90 meters above the ground, is the main building block of Houdin's pyramid theory. It has been previously noted by pyramid experts, but never considered of great significance. To the French architect, it's vital to proving how the ancient Egyptian builders managed to turn the great stone blocks, as they gradually shoved them up the internal ramp. In 2008, Brier and a National Geographic camera crew - together with an expert mountaineer - climbed up to the notch, squeezed inside and entered a narrow L-shaped room, *which was exactly where Houdin had predicted it would be*. It was in hollow corner sections such as this, he claims, that the pyramid builders spun the blocks 90° - for the ascent of the next side - using a crane.

4. CONCLUSION

Most ramping methods, while able move the blocks of approximately the bottom two thirds of the structure, fail in transporting the blocks at the top of the pyramid. Because of the geometric limitations of the pyramidal shape, each increase in vertical distance reduces available width and depth of the superstructure on which to place a ramp. These problems of reduced space encumber most ramp hypotheses. The ramping method that can complete the structure alone (the large straight ramp) is criticized for the tremendous amount of material needed for its construction. While there are problems specific to various ramping hypotheses, there are also shared limitations. These common problems involve issues of pyramid cloaking, the archaeological record, and the ability of the temporary ramp structure to endure the elements. The authors claiming that the structure was constructed through outward and upward in layers, starting with the core and ending with the facing stones poses an interesting and, yet, damaging circumstance regarding the construction and efficiency of ramps. More often than not, problems with back sighting and cloaking are used to question the feasibility of a ramping technique. It is difficult to establish a good critique using this form of argument and its foundations are often conjectural due to the problems inherent in quantifying what type of backsighting was needed, if any, by the ancient Egyptian pyramid builders. The remains of the ramps found within the pyramid complex are small. Using these examples to disprove ramp hypotheses can lead to ambiguous conclusions. These ideas of pyramid construction add tremendous amounts of labor to the construction of ramps. Under this type of construction, a ramp or ramps would have to be built to construct each stage, adding much more labor to the construction effort.

Let's take a look at the Houdin's theory. Has the French architect really "solved" ancient Egypt's greatest mystery? His conclusion, based on extensive projections using advanced 3D-modelling computer programs, is that an external ramp was used to erect the first 43 meters of the structure, then an inner ramp built into the fabric of the pyramid itself was used to lift stones (taken from the dismantled external ramp) towards its 147-metre apex. Many of Houdin's ideas still rest on mere hypothesis, but a few concrete finds have thus-far backed up his claims. Houdin believes that a technique as simple as placing an infrared camera in front of the pyramid and recording subtle differences in its interior materials and temperatures could be all that's required to finally prove, beyond all doubt, that an internal ramp exists.

If one model stands out as the only design that can perform the task within the parameters of time and space, materials, and available technology; and it fits the historical and archaeological record, then it can be considered more plausible than the other levering methods.

5. REFERENCES

[1] Mencken, August. (1963) Designing and Building the Great Pyramid. Baltimore: *Schneidereith & Sons*, 51-54.

[2] Guirlinger, Scott. (1999) The Egyptian Pyramids: Theories of Construction. Pensylvania: *for the course ARCH 316*, 10-16.

[3] Prevos, Peter. (1997) Pyramid Construction. Amsterdam: *a desk study*.

[4] Lepre, J.P. (1990) The Egyptian Pyramids. North Carolina: *McFarland & Company,Inc.*, 235-260.

[5] Piazzi, Smyth. (1880) Our Inheritance in the Great Pyramid. London: *Novello, Ewer&Co*, 331-413.

[6] Nova. (1997) This Old Pyramid, Transcript. PBS *airdate, electronic document*: http://www.pbs.org/wgbh/nova/transcript/1915mpyramid.html

[7] Dunham, Dows. (1956) Building an Egyptian Pyramid. Boston: *Archeology, Vol.9, No.3*, 159-165.

[8] Wegener Sleeswyk, André. (1985) Pyramid Buildings as an Integrated Process. Pennsylvania: *Taylor & Francis, History and Technology, Vol.2, Issue 2*.

[9] Crozat, Pierre. (2004) Engineering of Pyramids. Paris: *6éme Congres Europeen de Science des Systemes*.

[10] Macalay, David. (1975) Pyramid. Boston: Houghton Nifflin Company, 5-55.

[11] Sullivan, Elaine. (2008) Construction Methods and Building Materials. London: *Digital Karnak*.

[12] Malcom, Jack. (2009) Building the Great Pyramid of Giza: Jean-Pierre Houdin's Internal Ramp Theory. *Online article*: http://heritage-key.com/egypt/building-great-pyramid-giza-jean-pierre-houdin's-ramp-theory

[13] Hodges, Peter. (1989) How the Pyramids Were Built. *Element Books*.

[14] Brier, Bob. Houdin, Jean-Pierre. (2008) The Secret of the Great Pyramid. Smithsonian; First Edition, 12-31; 139-190.