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Abstract: Pyramids, symbols of the Ancient Egyptian civilization, are visited by tourists and studied by researchers from all around the world. However, the techniques used by Ancient Egyptians to construct the pyramid, specifically, how such a tall structure could have been constructed from huge blocks of stone with the limited productive forces at the time, remains a mystery to the world. Though numerous theories, such as the use of ramps, levers, pulleys, fluid buoyancy, and cast-in-place concrete, have been proposed in academia, no consensus has been reached to date. Based on mechanical principles and the productive forces available at the time, the famous Pyramid of Khufu is used as a case study in this paper to propose a theory of pit-aided construction. The main steps include the digging of the pit, the transportation of stone blocks into the pit, the layer-by-layer construction, and the layer-by-layer filling of soil until the top of the pyramid is completed. The main idea of the pit-aided construction was to use the self-weight of the stone material to achieve the transportation of stone blocks by converting potential energy to kinetic energy, thereby avoiding the large amounts of work that must be done to elevate the huge blocks of stone. The proposed theory of pit-aided construction is consistent with the cultural custom of burial that is associated with tomb construction, namely laying the deceased to rest through burial, and is also consistent with the productive forces available in Ancient Egypt at the time.

Keywords: Egyptian Pyramids, construction techniques, pits, mechanical principles, gravitational potential energy

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Introduction

Pyramids are iconic symbols of the Ancient Egyptian civilization, as well as a national icon and symbol of Egypt. Being square pyramidal in shape, Egyptian pyramids take the shape of an isosceles triangle when viewed from any of the four sides—much resembling the Chinese character "Jin (金)." This resemblance gave rise to its Chinese name "Jinzita (金字塔)" (lit. "Jin-character pagoda"). To date, approximately 110 pyramids of various heights and sizes have been discovered in Egypt. Of these pyramids, the Pyramid of Khufu, which is lauded as one of the "Seven Wonders of the World," is the largest, most magnificent, and most mysterious pyramid. It attracts visitors from all over the world. The Pyramid of Khufu, initially standing at 146.59 m high, or as tall as a 40-story building, was the highest building in the world prior to the construction of the Eiffel tower. It was built from 2.3 million blocks of stone weighing an average of 2.5 metric tons each, with the heaviest block weighing over 50 metric tons (Jin, 1978).

The purpose, techniques of construction, and builders of the pyramids are of strong interest in academia, drawing numerous archaeologists to conduct field surveys, excavations, and research, and even leading to the creation of a new field of research—"Pyramidology." In spite of the large amounts of research contributions by academics, many unsolved mysteries remain regarding the Egyptian pyramids. One such mystery is the construction techniques used: given the productive forces that were available at the time (tools, ropes, mechanisms, etc.), how did Ancient Egyptians manage to transport such a large number of huge stone blocks to a height of over 100 m, and to produce a tightly joined structure that has lasted for over 4,000 years? No consensus has been reached to date, though various theories have been held by different academics. While some academics proposed that ramps were constructed to aid the transportation of stone blocks, others suggested that levers were used to pry the stone blocks upwards one level at a time (Mark, 1997), or that stone blocks were raised using fixed pulleys (Kato, 2020) or even kites (Yu, 2004). In addition, there are academics who believe that the stone blocks used in the construction of the pyramid were not naturally formed, but rather cast in-situ using limestone rubble and cement (Joseph, 1988). Some have even proposed theological theories that the pyramids were constructed by aliens, survivors of the lost Atlantis, or a Berber tribe from the Atlas Mountains in northern Africa (Wu, 1986).

By summarizing and analyzing existing theories, as well as considering the productive forces available and the social formation at the time of Ancient Egypt, this paper proposes the theory of using an excavated pit for pyramid construction based on mechanical principles and presents the construction method and procedures using the Pyramid of Khufu as a case study. The key idea of this method lies in transporting stone blocks downwards, as opposed to the traditional approach of raising the stone blocks. This way, the gravitational potential energy of the stone block can be converted to the kinetic energy of its downward sliding motion, thereby greatly reducing the energy required for its transportation. Being consistent with both the productive forces available at the time as well as the cultural custom of burying tombs underground, this theory provides a new train of thought and perspective for uncovering the mystery behind the construction of the pyramids.

A Review of Traditional Construction Techniques and Theories

In this paper, only construction methods existing in the material world will be explored. In other words, mythological and theological theories, such as theories of pyramid construction by aliens, God, surviving residents of Atlantis, or a Berber tribe from northern Africa, that do not lie within the purview of scientific research will thus not be discussed. As some consensus has been reached on the origins and means of transportation of the rock material, these will also not be further discussed in this paper.

Ramp Principles

Ramp principles, which have significant influence in academia, refer to the simultaneous construction of a long earthen ramp on the side of the pyramid during the pyramid construction process to allow workers to transport stone blocks along the ramp and up the layers of the pyramid to the appropriate height. Though seemingly logical, this theory is unrealistic. Academics have raised numerous questions, mainly focusing on two areas. First, the construction of the ramp is a task of immense proportions. Craig B. Smith (2004) pointed out that a ramp leading to the top of the Pyramid of Khufu would be at least half a mile long and would require more than three times the material needed for the pyramid itself. J.P. Lepre (1990) suggested that a ramp with a length of over 1,000 feet would require more than 50 percent of the volume of the pyramid itself. Second, although the construction of ramps requires large amounts of materials such as stone and soil, no archaeological evidence of construction materials used in ramp construction has been found.

Some scholars have revised the ramp principle on this basis, proposing the spiral ramp, i.e., a ramp that winds up and around the exterior of the pyramid to its peak. Nevertheless, two obvious loopholes remain in this theory. First, the construction of a spiral ramp up to its present location can only be completed after the completion of the top of the pyramid. Otherwise, the structure can easily loosen, affecting the later stages of construction. Second, a spiral ramp also needs to be about 1,600 meters long and requires large amounts of materials, leading to the same issue: the lack of archaeological evidence.

The French Architect Jean-Pierre Houdin proposed that a 43-meter-high ramp could be first constructed along the exterior foundation of the pyramid to allow for the transport of stone blocks during the construction of the base of the pyramid. Then, a spiral ramp would be constructed within the interior of the pyramid up to its peak at a distance of 10–15 meters from the exterior wall to be used for the transport of stone blocks from 43 meters to the top of the pyramid (Peng, 2007). Houdin posits that this inner ramp remains in the pyramid till this day and estimated that such a method of constructing the Pyramid of Khufu would require only 4,000 workers instead of 100 thousand.

However, no supporting archaeological evidence has been discovered to this day; furthermore, such a method is mechanically infeasible.

Lifting Principles

Aside from ramp-based transport, some academics have proposed other lifting mechanisms that may be used in the construction of pyramids. Mark Lehner (1997) believed that levers were used to pry stone blocks upwards through the layers of the pyramid during its construction; Gerard C. A. Fonte (2007) agreed with this theory and presented schematics for constructs such as a cantilever support to reduce friction in the lifting process. Akio Kato (2020) believed that space was reserved for a "central well" during the pyramid's construction to allow stone blocks to be lifted through the well. This was accomplished through fixed pulleys, with one end of the rope tied to the stone block to be lifted and the other to an empty basket. Smaller stones were placed in the basket until the total weight of its contents exceeded that of the stone block tied to the other side of the rope, thereby raising the stone block. He further pointed out that it was precisely due to the need to set aside space for the "central well" to allow the lifting of stone blocks that the King's chamber, the Queen's chamber, the Grand Gallery, and other passages were all located at least 7 meters away from the central axis.

Based on an Ancient Egyptian painting of a large bird pulling an object on the ground, Maureen Clemmons proposed the idea that stone blocks of the pyramid were lifted using a kite-lifting technique. The advantages of a kite-lifting technique are that no large ramps are required and that it is convenient for horizontal transportation. However, Gerard (2007) discovered through aerodynamic calculations that using kites to lift stone blocks was impossible. First, the wood and fabric available at the time could not support the weight of the huge stone blocks. Second, raising stone blocks of this size requires very strong winds, which do not occur frequently. Third, even with winds that were strong enough to provide the necessary lift, construction workers in Ancient Egypt could not have been capable of accurately controlling the stone blocks during transportation. In addition, some have proposed using fluid buoyancy to transport rocks: by tying stone blocks to sheepskin bags filled with air, the buoyancy exerted by the water allows the stone blocks to be lifted to a predetermined height. However, this approach is neither feasible nor operable mechanically.

Cast-in-Place Concrete

By analyzing the chemical composition of the pyramid's stone blocks, the French chemist Davidovit Joseph (1988) hypothesized that most of the stone blocks used in the construction of the Pyramid of Khufu are made of concrete cast from about 93 percent of limestone rubble and about 7 percent of cement. Additional evidence supporting this theory is the single long strand of human hair found in a stone block (Wu, 1986). The central idea in this theory is to break the whole into pieces, thereby circumventing the issues associated with cutting, transporting, and lifting large numbers of stone blocks. The theory is also able to explain how the different stone blocks were able to fit so precisely and closely together. However, some academics question this theory and believe that

Egyptian pyramids could not possibly have been made of cast-in-place concrete for three reasons. First, as the time required to cut the stone into rubble is approximately a third more than that required to cut the stone into regular-sized whole blocks of stone, Ancient Egyptian workers need not spend large amounts of time to first break the stones apart and then cast the pieces. Second, the casting process requires the repeated assembly and disassembly of formworks, which takes almost as much time as that needed for the transportation of large stone blocks. Third, cement casting technology was not yet available in 2,500 BCE (Gerard, 2007). The antiquarian Mukhtar pointed out that it was absolutely impossible for Ancient Egyptians to abandon the naturally available stone blocks in favor of fabricating 2.3 million artificial stone blocks through complex processes; moreover, the quarries found in the vicinity and on the eastern bank of the Nile River have already confirmed the source of the pyramid's stone blocks (Wu, 1986).

Method and Procedure of Pit-Aided Pyramid Construction

The method of constructing the Egyptian pyramids must first be mechanically feasible, and then also be consistent with the knowledge and productive forces available at the time. To date, all the construction techniques proposed in academia have been mechanically unsound; at the same time, these techniques require a level of productive forces surpassing that available in Egypt more than 4,500 years ago. Hence, they are nothing more than fantasies and science fiction. The pit-aided construction technique mainly consists of pit excavation, the downward transportation of stone blocks along the side of the pit, the layer-by-layer construction using stone blocks, and the filling of soil to the top of the pyramid. The fully constructed pyramid was entirely or mostly buried underground. Over the years, floodwaters from the Nile River washed the soil and sand surrounding the pyramid away, gradually exposing the pyramid which was then found and preserved by later generations. This approach is mechanically sound and consistent with the actual circumstances in Ancient Egypt, which can help to dispel myths and other nonsensical theories. In this paper, the Pyramid of Khufu is used as a case study to showcase the main method and procedure of pyramid construction by the Ancient Egyptians.

Pit Excavation

More than 4,500 years ago, the Ancient Egyptians had already begun making use of tools such as wooden shovels, stone shovels, copper shovels, and bronze shovels to facilitate digging and tillage. The sand pit used for pyramid construction takes the shape of an inverted square frustum that narrows downwards, as shown in Figure 1. The bottom of this sand pit is shaped like the pyramid's base, i.e., a square, with a side length of a. The area of this square is slightly larger than the base area of the Pyramid of Khufu (230m×230m), and the excavation depth h is basically the same as the initial height of the pyramid (146.59 m), i.e., h =146m. The slope inclination angle α must be less than 52° to prevent the natural collapse of the slope. Ancient Egyptian workers would have installed wooden stairs made from logs, branches, and sedge, which serves the dual purpose of reinforcing the slope

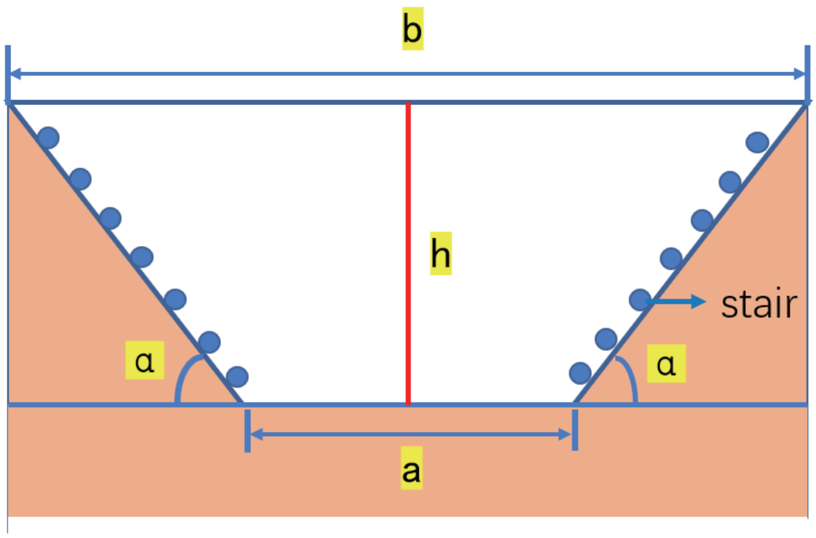

Figure 1: Schematic of the sand pit used in the construction of the Pyramid of Khufu

and providing a path to facilitate the movement of Ancient Egyptian workers up and down the slope.

To support the immense weight of the pyramid, the bottom of the sand pit must be comprised of hard materials such as stone or hard soil. If the need arises, additional underground tombs and passages, such as those present in the Pyramid of Khufu, may be created by further excavating (or chiseling) downwards.

Layer-by-Layer Construction

By sliding the prepared stone blocks along the ramp to the bottom of the sand pit, workers only need to apply a relatively small force to push or guide the stone blocks in the correct direction. As compared to lifting the stone blocks upwards, sliding the stone blocks downwards can significantly reduce the effort required by the workers. Taking advantage of the self-weight of the stone blocks for their downward transport, converting potential energy to kinetic energy, is entirely feasible from the point of view of mechanics, and would have greatly reduced the energy needed to move the stone blocks. After the stone blocks are transported to the bottom of the sand pit, workers could then use simple tools such as levers, ropes, pulleys, and wooden poles to transport the stone blocks to their designated locations, where they are laid down per design, layer by layer. After the completion of the second layer, the pit is filled with soil or sand up to the height of the first layer; after the completion of the third layer, the pit is filled with soil or sand up to the height of the second layer. This process of filling up the pit as the construction progresses is repeated until the top of the pyramid is completed, as shown in Figure 2.

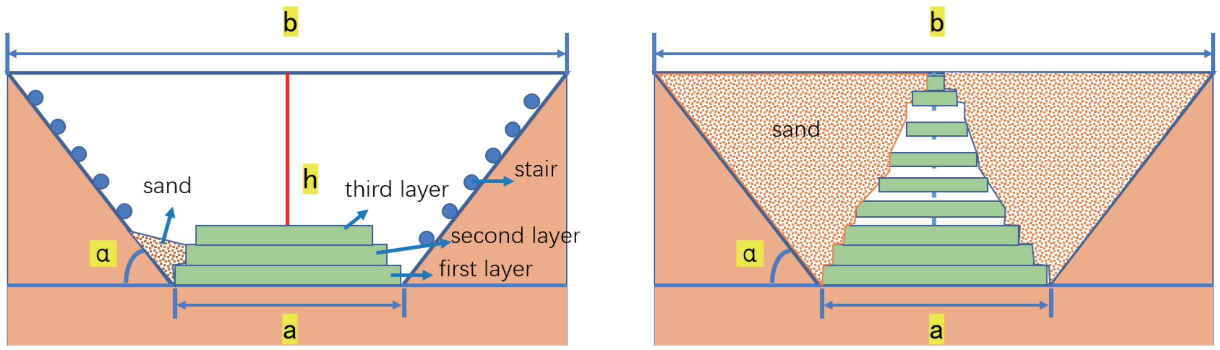

Figure 2: Schematic of the layer-by-layer construction of the pyramid

The pyramid could be built layer by layer from its base towards its top, with the construction of internal structures and outer walls proceeding simultaneously. Internal structures such as the King's chamber, the Queen's chamber, and the Grand Gallery were built with finely polished stone, while the external façade was constructed from roughly polished stones. While roughly polished stones may be obtained with simple tools such as rocks and copper tools, a more precise means of polishing is required for finely polished stones. To achieve a fine polish, the Ancient Egyptians placed the stone block in water and moved the stone block back and forth against a slab of hard stone using manpower or animals. The resulting flat and smooth surfaces allowed the stone blocks to fit seamlessly together. This wet polishing process, shown in Figure 3, reduces the friction and force needed to move the stone block, allows for faster polishing, and improves the flatness of the polished stone block.

Exposure of the Pyramid

Pyramids constructed by the pit-aided technique were either entirely or mostly buried under the sandy soil. So why are the pyramids currently exposed? This is because the surrounding sandy soil has been eroded away by floods and wind, causing a lowering of the ground level. Most Egyptian pyramids are situated close to the Nile River, which is prone to floods under the influence of the Indian Ocean monsoons. The huge impact forces of these floods washed the sandy soil surrounding the pyramids away. After years of erosion by floods, the pyramids gradually became exposed. The clear traces of water erosion on the exterior façade of the Pyramid of Khufu provide evidence for this theory. In addition, wind erosion also hastened the

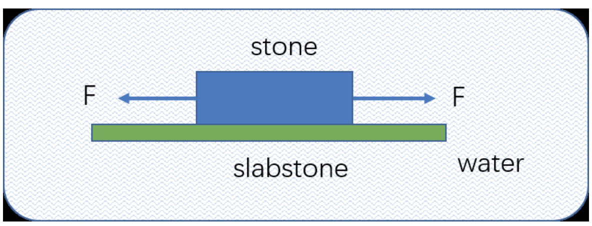

Figure 3: Schematic of the wet polishing of stone blocks

lowering of the ground level and increased the speed at which the pyramids were becoming exposed. The traces of water erosion found on the Sphinx of Giza in Egypt provide further circumstantial evidence. Egyptians living thousands of years later discovered the partially exposed pyramids and started manually excavating the site out of curiosity until the pyramids were fully exposed. These pyramids were protected and inherited till this day as iconic symbols of the Ancient Egyptian civilization.

Relevant Supporting Evidence for the Pit-aided Pyramid Construction

Pit Excavation Is Consistent with the Cultural Custom of Tomb Building

There are many different opinions about the purpose behind the pyramids' construction. Some believed that it was to foster loyalty and confidence in Ancient Egyptian youth (Gerard, 1998), others believed that the pyramids were energy receiving towers, and yet others believed that the pyramids were monuments or markers with which farmers divided farmland. However, the mainstream view is that pyramids were tombs (Luo, 2001). Ancient Egyptians typically used in-ground burials for the disposal of dead bodies, and even the few that were mummified were also eventually buried. As such, the pit-aided construction of pyramids is consistent with the cultural custom of burial that is associated with tomb construction.

Pit Excavation Is Consistent with the Level of Productive Forces at the Time

The biggest question about the pyramids' construction technique is how the huge blocks of stone were transported to a height of more than 100 m. All previous studies in academia have revolved around lifting the stone blocks, which requires work to be done against gravity. Owing to the immense weight of the stone blocks and the significant height the blocks needed to be raised, a large amount of work would have been required. For the level of production available in Ancient Egypt in 2,500 BCE, this poses a great challenge and is infeasible from the perspective of mechanics. Academics have tried to provide numerous lifting devices and strategies from the perspective of mechanical advantage. However, though these techniques are feasible in today's context due to the availability of high-power lifting devices, it would have been impossible for Ancient Egyptian workers to make use of such techniques. Without iron tools, which were not available in 2,500 BC, the then-available tools such as wooden or copper pulleys, levers, and grass ropes could not have possibly supported the weight of the stone blocks. On top of avoiding having to do an immense amount of work against gravity to raise the blocks, the pit-aided technique was also able to make use of the stone block's own weight to slide them into the appropriate positions. By converting the gravitational potential energy of the stone blocks to the kinetic energy needed for their transportation, a fundamental transformation from the "impossible" to the "possible" was achieved.

Smaller Project Quantity Compared to Other Techniques

Though the pit-aided construction resolved the problem of raising the massive stone blocks, it also requires the additional step of pit excavation. The project quantity of pit excavation is directly determined by the volume of the sand pit, which is a function of both the volume of the pyramid and the slope inclination angle (α). A smaller value of α results in a more stable slope but increases the project quantity of pit excavation; a larger value of α decreases the project quantity but increases the likelihood of a slope failure. The relationship between the volume of the sand pit (V) and the tangent of the slope inclination angle (tan α) is linear, and is given by the following mathematical equation:

$$V = \frac{1}{3}b^2h + \frac{1}{6}a(b^2 - a^2)\tan\alpha$$

where h is the depth of the sand pit, a is the side length of the square base of the sand pit, and b is the side length of the square opening at the top of the sand pit.

Let us analyze the amount of soil that needs to be excavated. Figure 4 shows the relationship between the volume of the sand pit required for the construction of the Pyramid of Khufu and the slope inclination angle. As can be seen, the volume of the sand pit rapidly decreases with increasing slope inclination angle: the sand pit volume at an angle of inclination of 60° is only 30 percent of that at an angle of inclination of 30°. Hence, a relatively larger bank inclination angle should be selected to reduce the sand excavation volume. Taking the critical angle of repose of 52°, the calculated sand

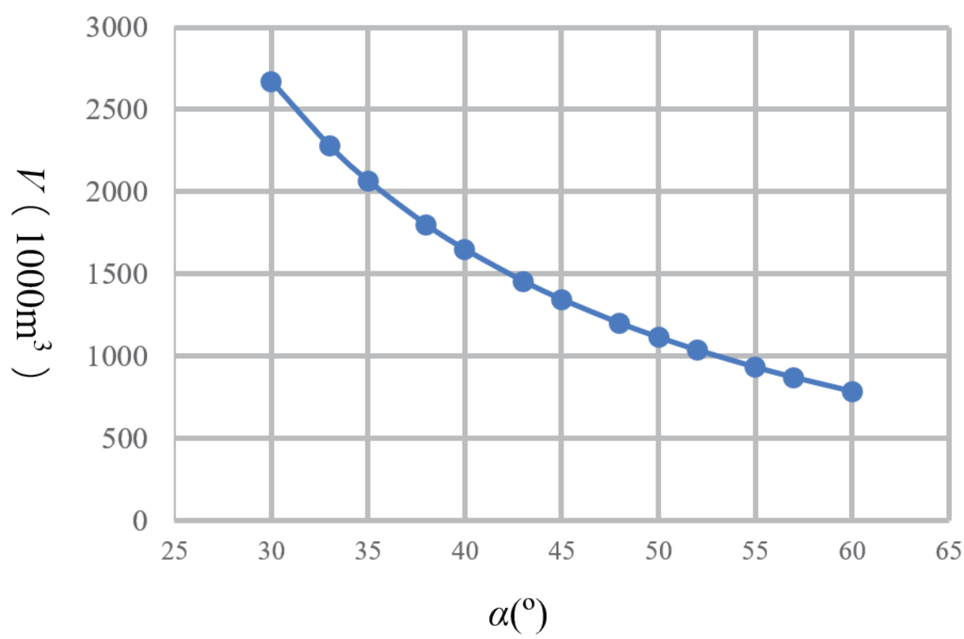

Figure 4: Relationship between the pit excavation volume and the slope inclination angle

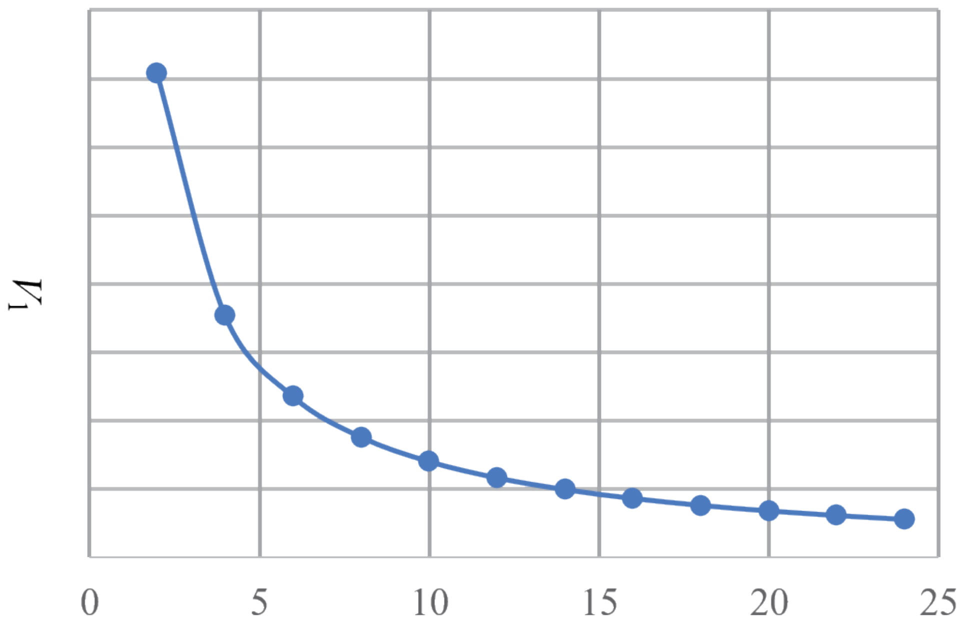

Figure 5: Variation of the ramp volume with the ramp inclination angle

excavation volume amounts to approximately 10 million cubic meters. Although a sand excavation volume of 10 million cubic meters is not a small project even in today's context, it is nevertheless entirely feasible. Assuming that each worker can excavate ten cubic meters of sand per day, the entire pit excavation can be completed by 10 thousand workers in 100 days, or about three months.

Let us review the ramp-assisted construction technique. Figure 5 shows the variation of the ramp volume (V1) with the ramp inclination angle (β). There is an inverse relationship between V1 and the tangent of (β). A larger inclination angle reduces the volume of sand required for the ramp but increases the difficulty of transportation; a smaller inclination angle results in greater ease of transportation but increases the volume of sand required for the ramp. Academics have estimated that, given the productive forces available at the time, the maximum ramp inclination angle that would have allowed the transport of such a large number of heavy stone blocks would have been 8° (Peng, 2007). Taking the ramp inclination angle to be 8° and the width of the ramp to be half the side length of the pyramid's base, calculations suggest that the construction of the Pyramid of Khufu would have required a ramp volume of about 9 million cubic meters. Considering the compaction of the ramp by the immense weight of the stone blocks during their transportation, the bulk density of the ramp would necessarily be higher. Therefore, the volume of sandy soil required for a ramp suitable for the construction of the Pyramid of Khufu is approximately the same as the excavation volume of the pit-aided construction technique. For the pit-aided construction technique, the remaining construction process after the excavation of the sand pit is easy. For techniques based on ramp principles, however, a large number of huge stone blocks still need to be transported up the ramp and stacked. Therefore, the time required for the pit-aided construction would be far less than the 100 thousand workers and 20 years required for the ramp-aided construction technique that was estimated by the Ancient Greek historian Herodotus.

If a reduction in the construction effort is required, the depth of the pit need not be exactly the same as the height of the pyramid; instead, the depth of the pit can be slighter shorter than the height of the pyramid, thereby further reducing the project quantity of sand excavation. The shorter depth

Figure 6: A sculpture of Khufu

of the pit compared to the height of the pyramid will lead to a portion of the pyramid's top being exposed, which will also be consistent with the typical customary practice of leaving identifying features for tombs. Normally, the height of the portion exposed above the ground level will be no greater than 10 meters, and the volume of this portion constitutes a tiny fraction of the total volume of the pyramid. As such, the task of transporting stone blocks upwards is relatively easy and could certainly have been achieved by Ancient Egyptian workers. Naturally, the probability of this scenario is relatively low. During the pyramid's construction process, the Sarcophagus can be buried in the pyramid in advance, when Khufu was still alive. In this case, the Sarcophagus will not contain the actual corpse, which will be buried in locations such as the Valley of the Kings in Luxor, Egypt, but instead the clothing of the Pharoah. At the same time, a hidden passage to the tomb chamber will also need to be created when the excavated pit is filled with sand. This method is also very popular in China. As seen from Figure 6, the attire and demeanor portrayed in Khufu's sculpture reveal numerous oriental elements; in particular, there are very clear Chinese characteristics. Since antiquity, in-ground burial has been the predominant means of final disposition in China, particularly for rulers, for whom large-scale underground tombs were constructed.

Conclusion

The Egyptian pyramids are wonders of the world, and their construction techniques remain shrouded in mystery. Previous studies have mostly interpreted the problem based on today's technological thinking and level of productive forces and have completely departed from the conditions at the time in Ancient Egypt. Based on mechanical principles and the level of productive forces at the time, a pit-aided construction technique was proposed for the construction of Egyptian pyramids in this paper. This technique is a breakthrough in the prevailing train of thought and is consistent with the authentic productive forces available in Ancient Egypt in 2,500 BCE and resolves the problems with mechanical feasibility and practical possibility. It subverts all previous methods and hypotheses and is suitable for dispelling the hypotheses based on mythology and aliens. To completely unravel the mystery of the pyramids' construction, we welcome interested academics to provide constructive feedback and critique; however, we are resolutely opposed to casual vituperation and senseless accusation. Let us walk hand in hand to reveal the mystery of the Egyptian pyramids and work together in pursuit of the truth.

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