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Egypt of the Pharaohs: Some case histories

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ABSTRACT: Forty-five centuries ago, pharaohs had to deal with many of the problems relating with our specialty. They did it with success and it would be ungracious to criticize the few mistakes related hereafter, when, recently, celebrated builders did not avoid the same errors.

It is for me a signal honour to be made a doctor honoris causa of one of the most ancient Universities of Europe, located in the capital city of Southern Italy where I have had so much pleasure contributing to work on the construction of the major port near the shores of ancient Sibari.

Dear Professor Viggiani, when you invited me to deliver this lecture, I was afraid you had not made the right choice. The "aging effect" improves the quality of clays not that of men: moreover I am not especially at ease in a foreign language. Nevertheless, apart from the pleasure of encountering old friend, I accepted this honour with the strong desire to join the homage being paid today to the memory of Professor Croce. He was a very good friend of mine and I always appreciated his courtesy as well as his culture: for him a stone was not a silent mass but something telling him stories of very old monuments. He was a humanist like those great architects of the Quatro Cento. I admired him and I wish to assure Mrs. Croce and his sons that we will keep his memory faithfully.

No branch of archeology has received, in recent years, more attention from scholars than the study of pyramids. Our learned Society and in particular our T.C. 19 cannot disregard such studies because the builders of monuments as ponderous as those pyramids had to deal with many of the questions relating to our specialty and it is not without interest to find out how the ancient Egyptians solved them. Already, those who were present in Cairo had the privilege of listening to a very interesting lecture given by Dick Parry.

1-PYRAMIDS:

In very ancient times and still today the tomb is, under certain circumstances, a shallow grave hidden under a heap of stones. What were the differences introduced by the Égyptians for the burial of their pharaohs? Of course, differences in mass and slopes: the volume of the Great Pyramid is no less than 2,500,000 m3 and the slope of almost all pyramids greater than 52 degrees, but it would be a mistake to think that the internal structure was totally different from a heap of stones: the pyramid was not at all made of a superimposition of parallelepipeds. The diagram in fig. 1 is to be discarded: only a small proportion of the stones were hewn with accuracy. The other differences are related to the use of mortar and to the depth of the funeral chamber, sometimes deep sometimes shallow. Fig. 2 illustrates that point as well as the development in size of pyramids from Djoser (2,900 B.C.) to Cheops (2,500 B.C.) at the apogée of pyramid construction.

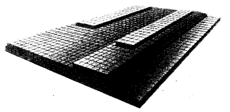


Fig. 1 Sketch to be discarded: a pyramid is not made of a superimposition of parallepipeds.

Finally, there were three main problems involved in their construction:

1-Soil bearing capacity
2-Slope stability
3-Funeral chamber stability

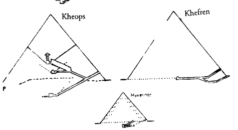


Fig. 2 Location of several funeral chambers

1-1 *Soil bearing capacity*

All pyramids were built on the libyan plateau, the Occident mountain where the sunsets and dies', along a band with an overall length of approximately 20 km (fig. 3). Over such a distance the geology varies, the weaker point seeming to be around Dashur where the soil bearing capacity was twice overestimated, at an interval of 800 years. The first time occurred under Snefru (2,600 B.C.). Very ambitious, the Pharaoh had in mind the construction of a very high pyramid (fig. 4), culminating at 140 meters with slopes of 60 degrees. According to Marogioglo and Rinaldi, two Italian engineers and Archeologists to whom we are indebted for very accurate drawings of pyramids, the soil there is a clay with flint pebbles. Work on the first design was interrupted at a height of 49 meters (the corresponding stress on the soil was then approximately 100 kPa); the base was then enlarged so as to give a smoother slope of 54,5 degrees, again reduced to 43,5 degrees as soon as the height exceeded the previous height of 49 meters. Very significant for us are the differential settlements shown in each descending corridor leading to the funeral chambers (fig. 5). The other proof of the insufficient carrying capacity of the soil is related to the pyramid of Amenemhet III of the XIIth dynasty, to the east of Snefru's pyramid, with its signs of subsidences in the funeral chamber. We refer to them in section 1-3.

As we see, the Dahshur site (hatched zone in fig. 3) was poorly chosen: Cheops took advantage of his father's error. The Great Pyramid (fig.6) was built on a solid eocène limestone. Nevertheless, on the border of the plateau on which the pyramid stands (fig. 7) there are some significant faults. Acting like a geomechanical engineering, Cheops hammered into them specially trimmed stones (fig. 8): every time I descend the small corridor (marked 2 in fig. 6) leading to the subterranean chamber, I cannot help stopping to admire the work of the pharaoh, our ancestor at a distance of 45 centuries.

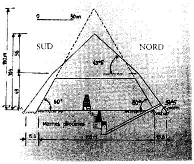


Fig. 4 The change in plans for the Dahchur South; -------shows the true pyramid as originally planned

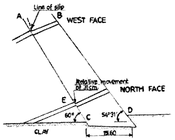


Fig. 5 Differential settlements between the new face at 54°30' and the original face at 60°

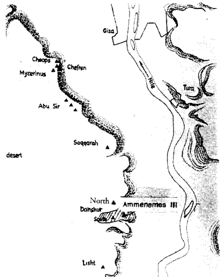


Fig. 3 Sketch map of lower Egypt

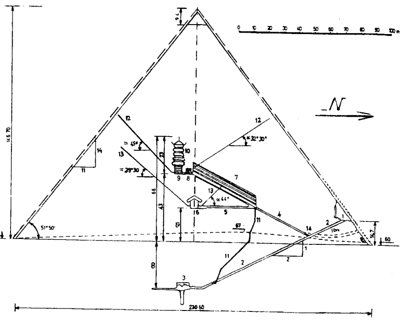


Fig. 6 North-South cross-section of the Great Pyramid

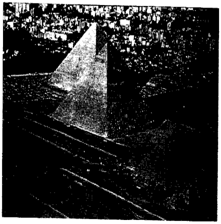
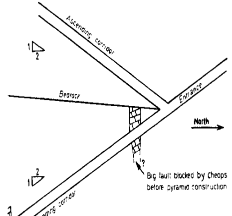


Fig7 The three Gizeh pyramids: in the background is the valley on the border of which was built the great pyramid.

1-2-Slope stability

As you probably know, there have been two kinds of pyramids: step pyramids (IIIrd dynasty) and, later on, true pyramids, perfectly tetrahedral. Djoser's step pyramid was the first one, revealing a very intelligent design (fig. 9). The problem was the long-term setting of the mortars binding the stones; this meant that the short-term slope stability was not totally guaranteed. Moreover, as he began the construction of a 300,000 m^3 pyramid with workers insufficiently trained, it was necessary to reduce drastically the number of hewn stones. Imhotep, Djoser's architect, decided to use them only for construction of a series of parallel and equidistant buttress walls (fig. 10), between which was deposited the débris from the stone cutting. Thus, so far away, it seems that Imhotep was not unaware of the existence of an active pressure. The upper part of the walls are shown on fig. 9; the stone size is small; they are not perfectly hewn resulting in great fatigue in the pyramid corners (fig. 11).



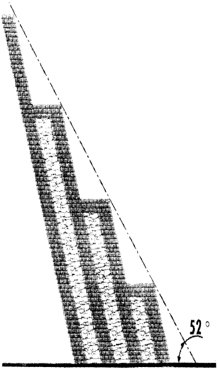


Fig. 10 Parallel internal buttress walls in the step pyramid.

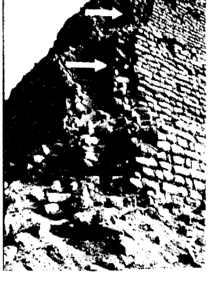


Fig. 11 In the corners, remains of buttress walls

Meidum pyramid, the last one of the dynasty, underwent three consecutive building stages; the first two attempts were superimposed step pyramids (fig. 12) each of them wirh buttress walls made of a

Nowadays, it has the shape shown in fig. 13 and 14, with buttress walls having been stripped. For what reason? Have some geomechanical principles been violated? Actually, the pyramid was indeed very heterogeneous, the material inserted between the buttress walls and under the external coating being of poor quality (Kerisel 1987); as a result, slip lines such as the one shown in fig. 15 would not have been impossible in the long-term. But it is also sure that the pyramid, like many others, has not escaped plundering: the whole of the outer casing of Tura limestone was stripped off the sides of all the great pyramids by Arabs in the Middle Ages, and it is very likely that at Meidum, which is far away from Tura, the fine limestones of the buttress walls was even more appreciated by robbers; so that the pyramid became a public quarry.

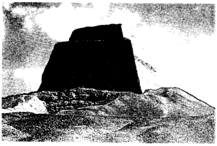


Fig.13 Remains of Meidum

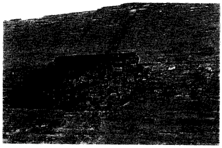


Fig. 14 The roughly quarried internal blocks to be seen through an opening in the North buttress wall.

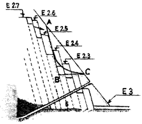


Fig. 15 The double black line shows the possible slip line of the unstable wedge ABC unstable in the long-term.

Later on, at the apogée of the pyramids, with the use of long slopes, no problems of stability occurred because the pharaoh gave up ancient low-quality mortars to adopt gypsum ones offering quicker setting times and higher resistance.

1-3-Funeral chamber stability

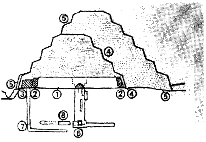


Fig. 16 The step pyramid, section looking south

Djoser's funeral chamber bears the mark of grandeur and wisdom: a shaft, approximately 7 m. square, was sunk into the limestone substratum to a depth of 28 m., the funeral chamber being situated at its bottom (fig. 16-6). The only geotechnical problem is now the stability of the dome (fig. 17) which extended into the lower central part of the pyramid just above the shaft : from time to time, a big block of stone falls into it. I have been asked to design the necessary consolidation work, which only awaits a substantial amount of money to be carried out.

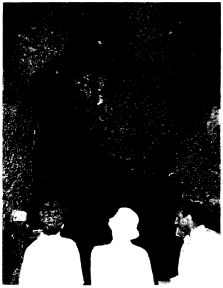


Fig. 17, The unstable dome roofing the funeral pit.

With the raising of the funeral chamber up to ground level, there was no accident, as long as its size was modest and the soil firm. Such was not the case in Dahshur. The first Dahshur pyramid had two funeral Chambers of significant size, one below ground Level, the other above. We already underlined the weakness of the soil and so we cannot wonder at the presence in the two chambers of a framework of thick cederwood beams to counteract lateral pressure on the walls. Not far from here, Amenemhet III built first pyramid the funeral chamber, which has also suffered from the effects of subsidence. Although the chambers and corridors were about 12m. below ground, the thick limestone blocks which lined their walls have, in places, sunk 10 cm owing to pressure from the weight of the pyramid.

We come now to the Great Pyramid (fig. 6), special in its internal structures: it contains, inside the pyramid itself, two chambers, the higher and greater one being called the King's Chamber; in it lies a sarcophagus. This chamber has suffered from distorsion: its south wall, while remaining vertical, has sunk approximately 5 cm, causing a similar distorsion in the upper chambers with flexure and rupture of their enormous beams. What was the reason for this disaster? The answer is the presence of two different kinds of masonry that were unevenly compressible under the weight of the pyramid: south of the wall is masonry of poor quality, such as that represented in fig. 18, with very roughly cut local stones sometimes laid without mortar, while the architecture of the chamber, overlying an incompressible foundation in Tura limestone (fig. 19) is of Aswan granite, one of the hardest rocks in the world. In proportion as the height increased, the settlement of the first masonry has caused the wall to slip downwards (fig. 20 et 21), a phenomenon of active friction we all recognize.

Fig. 18 Sight of a masonry of poor quality which can be seen in a small corridor dug by treasure-seekers at the bottom of a nich existing in the Queen's chamber

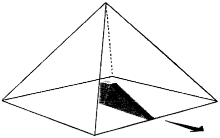


Fig. 19 The thick wall built with perfectly timmed blocks underlying corridors and chambers

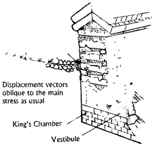


Fig. 20 Negative friction on the King chamber's wall, bringing a rupture in the upper beams

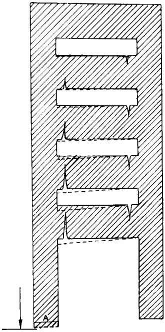


Fig. 21 Sketch of a quintuple portico subjected to a differential settlement.

Other example of accident relating to the existence of two very different masonries, may be used in the Mantou temple built by Aménophis III (Gabolde 1995). It was erected on a podium masonry in stones barely hewn or bound all over central zone, whereas the visible masonry around was very stiff, this difference resulting finally in a ruin of the temple.

2-PUBLIC WORKS

2-1-Dams

Under the IVth dynasty was built what can be called the world's oldest largest-scale dam. It was discovered 100 years ago; investigations have shown that it was overflooded at end of construction but its builders deserve great respect for their depth of vision in both design and construction. Fig. 22 shows the cross-section with the three traditional elements:

- a core of rubble, gravel and weathered material
- two rock sections on both sides of the core
- protection of the slopes, consisting of cut stones placed in steps

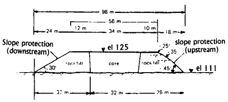


Fig. 22 Cross-section of the Sadd-el-Kafara dam

Fig. 23 Remains of the dam

The downstream side has an angle of 30°; the other side is steeper, with an angle of 45° in its lower part and 35° above. The original height of the dam was only 14 m.; of course, it was oversized and this indicates that no experience was available during the Old Empire. Figure 23 shows what remains of it: the unprotected middle section was quickly eroded by an exceptional wood.

2-2 Retaining walls

As early as 2500 B.C., the ancient Egyptians built very high retaining walls, such as those of the causeway connecting the funerary temple of the Great Pyramid to its valley temple; at one point they reached 125 m. in height. Unfortunately, we have no information on their structure. The only interesting remains of that type of construction are the relics of brick retaining walls for the building-ramp of the first Pylon of the temple of Karnak (fig. 24); it seems there were external counterforts, the remains of which can be seen in the lower part of the photo.

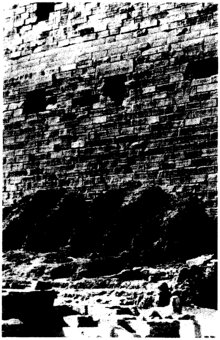


Fig. 24 Remains of a high retaining wall at Karnak

2-3 Sliding sleds and sliding boats

Transportation was a fundamental problem on ground as well as on water. Egyptians had sleds sliding ramps with moderate gradient as well as unloaden boats sliding on special slipways linking two levels of canal: the boats had no keel and the slipways had a shape that matched the boat hull. An example is the one found at Mirgissa (fig.25) beside the Second cataract of the Nile. In order to reduce the-pulling power needed to haul the boats up, a lubricating paste was interposed, made of a silty clay deposited by the Nile. Some authors have asserted that this lubrication was very efficient, with the sled sliding as if it were on ice, while others say the opposite. This gave me a reason for performing some experiments, which I performed in Paris on a silty clay having the same Atterberg limits. The problem is complex as is all those relating to friction. Details are shown in annex I in my recent book 'Génie et démesure d'un pharaon: Chéops'. Fig. 26 gives a brief summary: the average friction coefficient 0,15 is to be compared with 0,10 given by Aitkinson for sleds on wood rollers used by megalithic builders, a technique the Égyptian could not adopt due to the scarcity of fine timber.

Fig. 25 Slipway for unloaded boats at Mirgissa

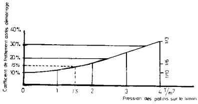


Fig. 26 Friction coefficient vs. pressure of the sled over the paste

CONCLUSION

As you see, the ancient Égyptian had to cope with many problems relating to our science. Even though they did not entirely succeed in all their enterprises, we have to admire them for their boldness and their first empirical understanding of active pressure, bearing capacity of rocks or soils, and sliding friction. Moreover, though the use of two different kinds of masonry led them to accidents, we must notice that the builders of romanesque and gothic monuments did not avoid the same errors. And in this country, the recent collapse of the civic tower of Pavia cathedral and probably also that of the Bell tower of San Marco, were due to the coexistence side by side of two kinds of masonries. Moreover, if my information is correct, such a coexistence is not to make easier the Pisa tower problems. Therefore, it would be ungracious for us to criticize the few mistakes we noticed in the very ancient Egypt; moreover we may say that Vitruvius was not totally right when he traced the ancient wisdom in the art of construction back to the Greeks and Latins: as I try to show you, the very first source of that wisdom lies with the Pharaohs.

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