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THE PERIODIC SYSTEM OF BUILDING A PYRAMID

By ALEXANDER BADAWY

THE building of a pyramid involved special problems, among which are cosmic orientation, avoiding twist and maintaining the angle of incline. We know that building proceeded in horizontal courses whose height decreased toward the top. A study of the cross-section shows a series of layers of equal width slanting at 75° around a central core.

Some of the constructional problems common to other types of monuments were rendered more difficult on account of the nature of the pyramid. The blocks were to be of a constant height throughout one course, and of relatively large dimensions. The size of the pyramid set another problem, if one thinks that about 115,000 blocks averaging 0·75 metres in height were required for only the casing of Khufu's pyramid. The transport of materials from the quarries was in itself an achievement, even though advantage was taken of the flood waters that allowed one to sail closer to the quarries in the east, and to the pyramid sites in the west. Unlike buildings located in the valley, the pyramids stood on the western desert plateau and the blocks transported on the river or canal boats had to be hauled up from the water's edge by means of sleds made to slide along a slippery ramp.

Causeways of pyramids were certainly used at the start of the work as constructional ramps. At least two ramps rose to the east and south sides of the pyramid at Meydum, in addition to its causeway, though there could have been, according to Petrie,[1] one more on the south and one or two more on the north, 'thus there were the needed five or six lines of approach for the material'. Constructional ramps existed at Giza (Khufu, Khaʿfrēʿ, Menkaurēʿ), Lisht (Amenemḥet I), Abusir, Saqqâra, and Dahshur. The theory of the design of constructional ramps for pyramids was studied by several scholars, particularly by Lauer.[2] To enable the masons to place the casing blocks and dress them after the building was completed, a foothold embankment of brick surrounding the pyramid as a carapace was built and raised successively at the levels of its courses. It could have measured about 13 metres in width.[3]

In contrast with most other monuments pyramids had to be cosmically oriented, as were sun temples. Edwards[4] has suggested that a plumb-line *merkhet* 'indicator', and a *bꜣy n ỉmy wnwt* 'palm of the observer of hours' were used, in conjunction with a circular wall the height of a man to determine the line midway between the positions of rising and setting of a northern star on a true horizontal datum line.

[1] *Egyptian Architecture* (London, 1938), 36.

[2] J.-Ph. Lauer, *Le Mystère des pyramides* (Paris, 1974), 279, fig. 62; I. E. S. Edwards, *The Pyramids of Egypt* (London, 1961), 205 ff.

[3] S. Clarke and R. Engelbach, *Ancient Egyptian Masonry* (Oxford, 1930), 126.

[4] Edwards, op. cit. 208.

Before dealing with the problem of avoiding twist and maintaining the angle of incline during the construction of a pyramid it is essential to examine the internal structure. All pyramids of the Old Kingdom show a series of slanting layers laid out on concentric squares around a prismatic core. These layers slanted 75°, the usual batter for the faces of mastaba superstructures. The faces of these so-called 'accretion layers' were made of better stone and masonry than their internal core, even to be smoothly dressed as at Neterikhet and at Meydum. Clarke and Engelbach[5] tentatively mentioned that it was 'an aid to the stability of the structure', or was the result of 'intense conservatism' or of a 'religious motive'. There is no way to investigate the internal structure of the three pyramids at Giza, but Borchardt deduced from the occurrence of well-dressed 'girdle-blocks' every ten cubits along the passage driven through existing masonry to the Great Gallery of Khufu that the system of accretion layers was followed there. Against this theory Clarke and Engelbach[6] raised, among other objections, the closeness of the layers and the consistent superb masonry in successive faces. The first argument loses much of its impact in view of the fact that Sekhemkhet's pyramid showed thirteen accretion layers, restored by Lauer as twinned layers, ten cubits thick for every layer. That the accretion layers were intended to enhance the stability of the pyramid is certainly true since forces within the structure are made to act toward the core. In addition they formed datum planes from which the process of construction could be constantly checked for accuracy. At Meydum, however, an error of 2·6 metres out of the square was detected by Petrie.[7]

The problem of maintaining accuracy throughout the lengthy process of construction of a pyramid that could rise 220 courses high (Khufu) must have been a major concern with the ancient architects. Twist in the pyramid had to be avoided, perhaps through checking the diagonals of the square plan with reference to datum points on the ground that would be projected on to the course.[8] Another major concern would have been to maintain the angle of incline. Two solutions were presented by Clarke and Engelbach: calculating the square at every course and describing it accurately on the masonry, or measurements by plumbing. The first method was seemingly not used by the builders (Clarke and Engelbach). As to the second one, the only suggested possibility was horizontal measuring to build up the slope 11:14 from a plumb line outside the foothold embankment. It was essential, however, to carry out this measurement over a considerable height, no less than 5 metres, and not on every course separately, to eliminate any cumulative error. Thirty shifts would then have sufficed for the tallest pyramid. Clarke and Engelbach concluded with the assumption that pits for plumb lines were built in the embankments. Lauer does not lend much attention to the problem, but mentions casually numerous large set squares, which would not have reached higher than two or three courses at a time. Measuring from a plumb line exposed to the wind or even sheltered within a pit would have presented serious difficulties and never could have been foolproof.

[5] Clarke and Engelbach, op. cit. 121.

[6] Ibid. 124.

[7] *Medum* (London, 1892), 6, 7.

[8] Clarke and Engelbach, op. cit. 125, fig. 136.

Since the Fourth Dynasty, and probably even earlier, a sighting device was used to control the batter of 75–76° or 1 : 4 in walls. Petrie[9] found in a mastaba at Meydum that there were vertical corner walls standing at foundation level. A double line marked in red sloped at 75° from the lower corner of each of the two inner faces. This indicated the trace of the plane of the battered face of the mastaba and formed a datum or guide-line for sighting and stretching a cord between both ends of the wall under construction. Horizontal lines marked with inverted triangles the levels at cubit intervals, thus providing at the points of intersection with the guide-line as many points as necessary for controlling the accuracy of batter during the progress of construction. This method of sighting with guide-lines at the corners of enveloping walls was used at all periods, as for controlling the vertical profile of the foundation platform of the shrines at Tell el-Rubʿa (Late Period).[10]

Pyramid builders did not forget earlier methods or types of construction, since they incorporated in the pyramid structure the massif, battered at 75°, characteristic of the mastaba. It is most probable that they built this massif, at least in the earliest attempt at Meydum, with the help of enveloping corner walls. (See fig. 1.) The faces of the massif were then well dressed. The process was repeated for every skin or accretion layer to the designed height, keeping also control throughout against twist by checking diagonals and axes of concentric squares. This process adapted to build the casing would have required corner walls inscribed with guide-lines sloping at 11 : 14 which could have enabled one to sight along the outer face at each course level, before it would be embedded in the rising embankment. (See fig. 2.) Such corner walls would have been of brick built on the embankment, tangent to the alignment of the casing or at some distance, to allow handling the blocks from the front.

Controlling the slope of the faces by sighting and measuring from corner walls would have presented an immense advantage over measuring from a plumb line in a pit built as deep as 17 metres in the embankment, as tentatively suggested by Clarke and Englebach.[11] Moreover the same corner walls would have served again for the dressing of the face, as the embankment would be lowered and a wooden scaffolding built to the height of the corner walls.[12] An alternative method, less satisfactory than that using corner walls, but improving upon the sunken pit system would be to build such a pit from the level of construction up. (See fig. 3.) From the guide-line marked on its walls horizontal measurements but no sighting could be made.

The practice of dressing the accretion faces was discontinued after Neterikhet and Snefru, and this allowed the whole pyramid to be built course by course throughout.[13] The system of building in periods up to the levels of the accretion faces, if correct, was certainly brought in conjunction with the corner walls corresponding to these levels. It was observed[14] that the casing blocks of Khufu's pyramid show a periodic decrease in height, which was explained as resulting from the use of certain amounts of stone renewed when exhausted according to a planned supply. It would be of interest to

[9] *Architecture*, 8, 29, fig. 10.

[10] D. P. Hansen, 'The Excavations at Tell el Rubʿa', *JARCE*. 6 (1967), 7.

[11] Op. cit. 126–8. [12] Ibid. 125. [13] Ibid. 121. [14] Ibid. 128.

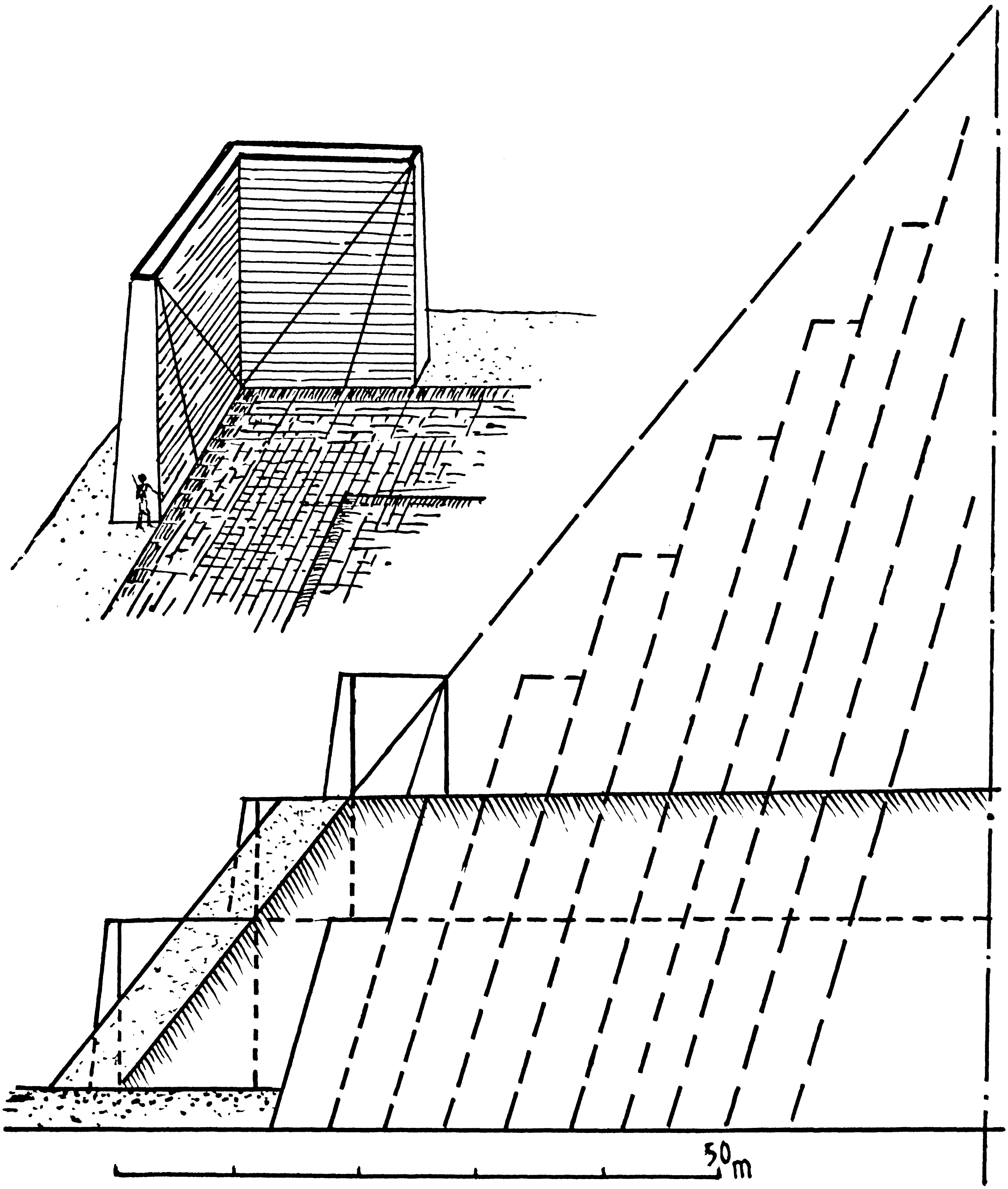

FIG. 1

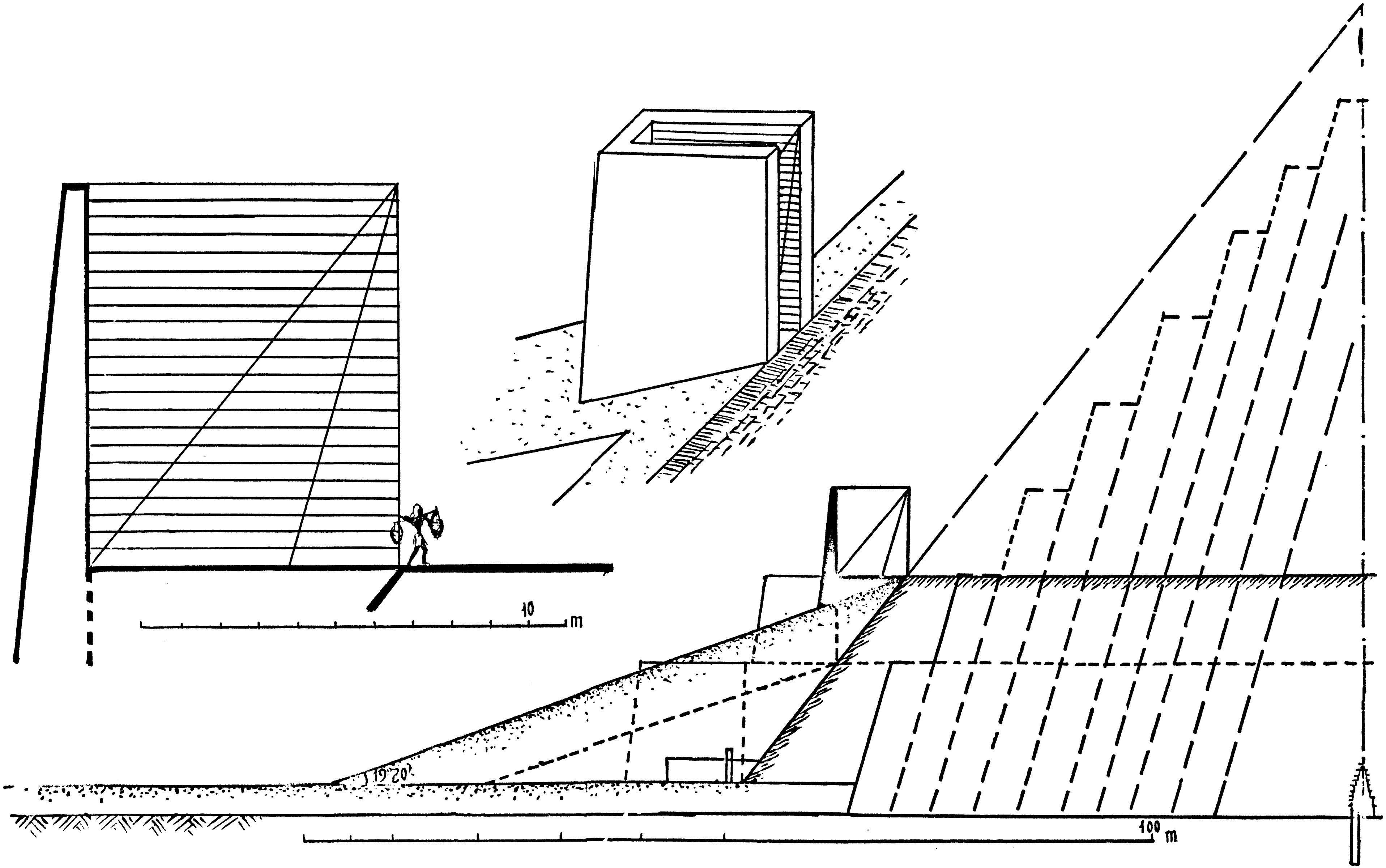

Fig. 2

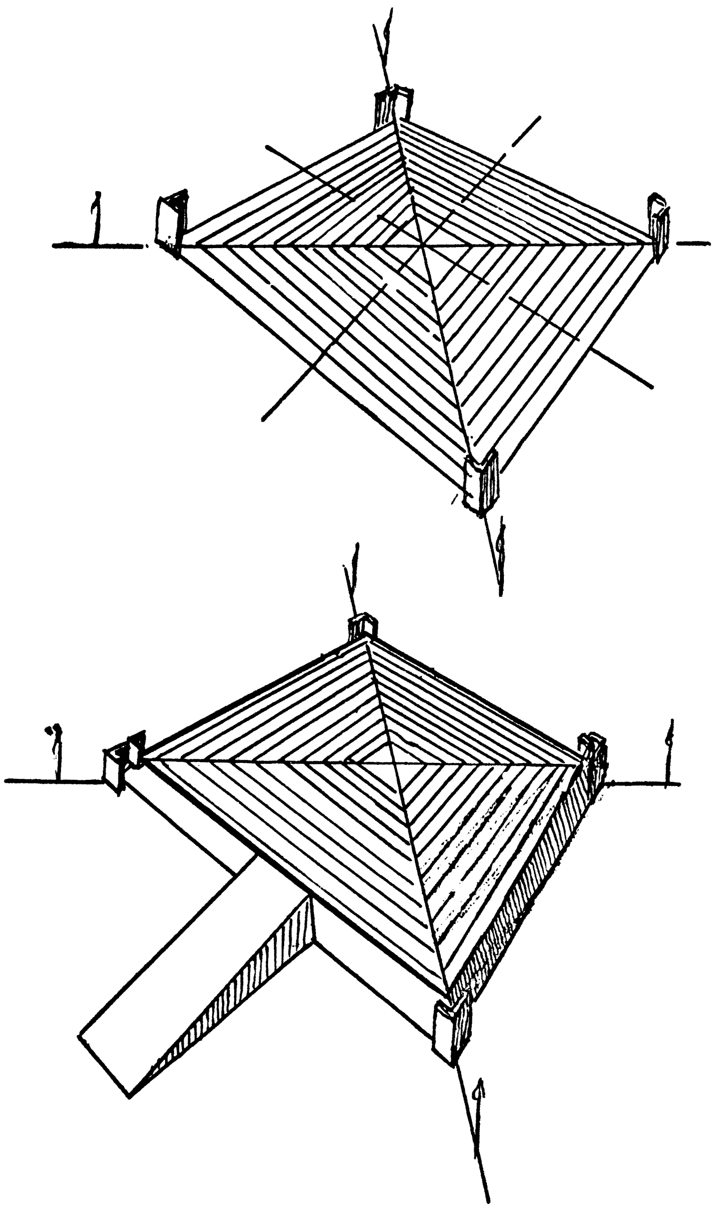

FIG. 3

investigate this periodic decrease in size, for there is strong presumption that it echoes the system of periodic construction determined by the steps of accretion layers.

Since the number of accretion layers seems to have been a determining factor in the periodic construction of a pyramid, it would have been of importance to keep them as few as possible. This number averages between 5 (Zawyet el-ʿAryan), 6 (Neterikhet, Saḥurēʿ), and 8 (Meydum) which means a corresponding number of 5, 6, to 8 shifts of corner walls or periods in construction. Keeping down the number of shifts meant less risks of cumulative errors. At the same time it meant taller corner walls. An examination of the section of Meydum pyramid shows that the heights of steps in accretion layers, and consequently those of corresponding corner walls, were from the bottom: 14·5, 10, 10, 10, 10, 10, 8, 8 metres for a constant width of 5 metres to the accretion layer. Building corner walls of such heights in brick presented no difficulty, for 10 metres seems to have been the average height reached by brick girdle walls from the Second Dynasty (Abydos, Hierakonpolis) throughout later periods (fortresses at Buhen, Miʿam).

Essentially structural as the purpose was to stabilize the huge mass and to provide datum planes during the process of constructing the accretion layers within the pyramid, the process could also have had, as hinted by Clarke and Engelbach,[15] a religious motive. Left apparent in the earlier step pyramids (Zawyet el-ʿAryan, Neterikhet, earliest Meydum), they formed a gigantic stairway which enabled the Pharaoh to mount up to the Imperishable Stars. In the *Pyramid Texts* this idea of a stellar destiny following an ascent on a stairway is clearly expressed: 'A staircase to heaven is laid for him that he may ascend on it to the sky' (no. 365).[16] This concept is found again in the hieroglyph 𓊎 sometimes described as a double stairway, but more probably representing the profile of a step pyramid and determining the verb *ỉꜥr* 'to ascend'.[17] The names of the pyramids of Snefru, Khufu, Dedefrēt, and Nebrēʿ indicate clearly a stellar connotation while those of Saḥurēʿ, Neferirkarēʿ, and Neferefrēʿ describe the stellar destiny of the *ba*.

[15] Op. cit. 121.

[16] Edwards, op. cit. 234; Alexander Badawy, 'Philological Evidence about Methods of Construction in Ancient Egypt', *ASAE* 54 (1956), 60; cf. *Pyr.* 1090 *c*, 1431 *b*, 1749 *b*.

[17] Edwards, op. cit. 234 f.; Alexander Badawy, 'The Ideology of the Superstructure of the Mastaba-Tomb in Egypt', *JNES* 15 (1956), 180–3.