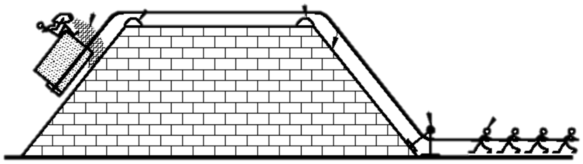

Building pyramids using very long ropes 3 April 2012

Robert M. Hartranft, Simsbury CT 06070,
John B. Hartranft

Making rope is a fully "scalable" activity: making a 2000 foot long rope uses the same process as making a 20 foot long rope. Suppose you ran such a very long rope up one side of a partially completed pyramid, across the top, down the other side, and out to a large pulling team, say with 200 men in the pulling team. Suppose each man could pull 50 pounds force. (This is not very challenging: if facing in the direction of pulling, just lean forward; or better yet, as in a tug of war, turn toward the pyramid and lean backward. An even easier way to sustain this force would be to attach cross boards to the pulling rope, and have the pullers pull it from a nearly sitting position, much like a rowing crew, but with no strain on their arms or backs; Pharaoh's OHSA inspector will be pleased!) However done, there is then a 10,000 pound force pull available at the other end of the rope, which will easily pull an average 5000 pound block up the partially complete side, across the partially complete top, and directly into place, even with a generous allowance for friction. (More realistically, 80 pullers per rope should suffice.)

Suppose the pullers move at 2 feet/second (1.36 miles/hour). The block will then move from the staging area at the base, up the side, and into place in a few minutes. (A representative pull would be 300 feet up the side and 200 feet along the top, consuming less than five minutes.) At most, the men will each be expending (2 feet/second) x (50 pounds force) / (550 foot pounds/sec/horsepower) = 0.18 horsepower, which is sustainable a few minutes at a time. Many pulling teams can work parallel ropes at the same time, so that net emplacement rates of at least one block per minute can be readily achieved. At this emplacement rate, working 10 hour days, 6 days a week, 50 weeks per year (or some comparable ancient Egyptian schedule), each year 180,000 blocks can be pulled into place. Completion of the estimated 2.4 million block structure on a schedule of less than 20 years should then be achievable, even allowing for inevitable delays. Oversize blocks can be emplaced using multiple ropes.

Even allowing for 20 pulling teams, only 1600 to 4000 pullers would be needed. If available, horses or oxen could also be used for pulling. Since the primary work is walking back and forth on the Giza plateau, conditions for personnel need not be murderous: it could be done by ordinary workers or by soldiers between campaigns. Since the same pulling paths could be used year after year, someone would probably decide to install ridged paving blocks to improve traction. Lightweight sun shades and abundant water for evaporative cooling in the summer would probably also appear.

Quick release wooden strongbacks would allow quick engagement of blocks in the staging area and quick release upon emplacement. Direction changes of the ropes at both upper edges of the pyramid and at the far base could be achieved with limited friction by passing them over gently curved, polished granite bearing blocks, probably with water as a lubricant. Friction between the moving block and the partially completed side and top would probably be reduced by pouring water ahead of the moving block, but no special skids or rollers are necessary: the new block would slide directly against the finish blocks on the sides and the lower blocks on the top.

This method requires no exotic technology: the ancient Egyptians clearly had heavy ropes. Nor does it require forgetting anything exotic: merely forgetting a "trick of the trade". Neither is there anything exotic to find: when complete, the very long ropes would simply be cut into shorter lengths and used for other purposes. The method works identically from the base to the capstone.

It seems likely that most of the blocks were quarried and shaped using copper or bronze saws and abrasives in an adjoining limestone quarry. This activity pace is harder to estimate, but it is also clearly achievable using technology they had, and it can also be done in parallel by many teams. If the block preparation process can be done by a comparably sized group, then the overall project should require no more than 8000 men, which is considerably more manageable and economically sustainable than the 100,000 man force sometimes postulated.

Footnotes

1. Due credit to others -- it's another ramp theory: Work in engineering is inevitably based on prior work and experience, and this speculation is no exception: it's another ramp theory. In this case, the side of the pyramid itself is the ramp for the blocks. This avoids the time and material for building separate ramps, ensures that the ramp is always ready for use for a new layer, and avoids the delays inherent in narrow ramps. Short ramps at the base reported by others would be useful for the first few layers, and thereafter could serve to transition blocks from horizontal to the slope of the pyramid side. If the casing blocks are placed during assembly on all four sides, and if the ropes are periodically shifted from side to side, the wear on the casing blocks will be evenly distributed, and will actually serve to polish their outer layer.

Several experts, including Jean-Philippe Lauer and Dr. J.D. Degreef, have proposed pulling from some location on the pyramid remote from the block itself. This is clearly possible, but we believe that pulling from the plateau instead has significant advantages, most notably avoiding needlessly walking up and down the pyramid, allowing simultaneous use of as many pulling teams as desired and of any size desired, and using a physiologically efficient pulling posture. Together with using the pyramid sides as ramps, we believe that the ancient Egyptians would have realized this early in construction. As best we can tell, however, we are the first authors to suggest this particular combination of techniques. We would be interested in seeing any earlier discussions of this combination.

2. Sliding friction of the block: Since limestone is a relatively soft material, any bottom surface irregularity on the sliding block will quickly erode to a smooth finish. Thereafter, there will be smooth limestone sliding against smooth limestone, lubricated by a slurry of limestone dust and

water, which is pretty slippery stuff. We plan on experimental verification, but our engineering judgment is that the resulting coefficient of sliding friction will be relatively low.

3. Sliding friction and wear on the rope: Our guess is that the pyramid builders provided a wear layer on the outside of the ropes, possibly as a tightly wrapped spiral of small diameter rope, replaced as needed. A somewhat higher technology alternative to polished granite bearing blocks for rope direction changes would be large wooden or granite pulleys or drums, probably with lubricated copper or bronze sleeve bearings. These would be similar in concept and technology to chariot wheels, which were well known then, although designed and sized for far larger loads. Such pulleys or drums would substantially reduce both friction and rope wear.

4. Power expenditure by pullers: A key element of our proposal is that the pullers just walk back and forth on the Giza plateau, rather than needlessly struggling up and down a ramp themselves. This means that we can estimate their maximum power expenditure fairly closely by looking simply at the sustained power delivered to friction and to elevating the block as it moves up the side of the pyramid. The estimate provided above is a maximum output of 0.18 horsepower for a period of several minutes at a time. (A very brief period of higher force and higher output to get the block moving would not be significant, and indeed, would be further eased by the natural elasticity of a long rope as it takes up tension at the start of a pull.)

To put this in perspective, consider the case of a modern, 180 pound man walking up typical seven inch rise steps at the measured pace of one step a second. (Go try this if it isn't obvious that such a pace is easily sustained; the exercise will do you more good than thinking about it!) Such an individual is doing (180 pounds) x (7/12 foot/step) x (1 step/second) / (550 foot-pounds/second/horsepower) = 0.19 horsepower. In other words, he is working harder than even the maximum required of pyramid block pullers in this model.

In practice, this means that the actual pulling crews could have been smaller, perhaps much smaller depending on the exact friction coefficients, or that assembly could have been even faster. This would certainly have been sorted out early in construction by experience, and thereafter done at an efficient overall pace.

5.Rope return variations: The simplest way to reset the pulling rope for another use would be to have a trailing section behind the new block, and pull the main rope back using a small group of men in the block staging area at the base of the pyramid. We can also envision a variety of other arrangements like staging areas on both sides of the pyramid, with the rope pulling another block up the opposite side as it is returned to its initial position. As with optimal crew size, we expect that the ancient Egyptians would have decided this based on experience early in construction.