PREFACE ..... II
ABSTRACT ..... III
CONTENTS ..... IV
Chapters

1. Introduction ..... 1
2. The model ..... 2

- Activities and building methods ..... 2
- The building process ..... 3

3. The size of the project ..... 5

- Pyramid and casing ..... 5
- Linear ramp ..... 5
- Spiral ramp ..... 7
- Other ramps ..... 7

4. The efficiency of manual labour ..... 7

- Definitions of unit performance ..... 7
- Quarrying ..... 8
- Excavation of a canal ..... 13
- Brick production ..... 14
- Transportation ..... 15

5. How many man-hours? ..... 26
6. Workforce and work schedule ..... 29

- Total workforce ..... 29
- Time ..... 30
- Building rate ..... 31
- Workforce for the various activities ..... 33

7. Combination of a ramp with levering ..... 36

- Conditions and summary of results ..... 36
- Transition between successive phases ..... 38
- The levering phase ..... 39
- Hindsight versus foresight ..... 43

8. Area per builder and hauling trains ..... 44

- Minimum area per builder ..... 44
- Available areas ..... 44
- Number of hauling trains ..... 46

9. Numerical example ..... 47
10. Discussion of basic data ..... 49
11. Placing the pyramidion (by K. J. Weber) ..... 50
12. The building materials (by K. J. Weber) ..... 53

- The Giza limestone ..... 53
- The Tura limestone ..... 59
- Granite ..... 59

13. Literature review ..... 59
14. Conclusions ..... 78
Appendices
15. Volumes of pyramid and casing ..... 80
16. Volume of linear ramp ..... 81
17. Volume of spiral ramp ..... 84
18. Manpower ..... 87
19. Workforce, time and rate ..... 92
20. Combination of a ramp with levering ..... 98
21. Area per builder ..... 102
22. Transportation ..... 104
23. How does it work for a mini-pyramid? ..... 110
Bibliography ..... 112
Illustration sources ..... 114
Tables attached
I. Unit performance for transportation - literature data ..... 115
II. Basic data ..... 116
III. Some results ..... 117
Figures attached
A.2.1 Exterior ramp - cross-section ..... 118
A.2.2 Exterior ramp - base areas ..... 118
A.2.3 Interior ramp - cross-section ..... 118
A.2.4 Staircase - cross-section ..... 118
A.3.1 Spiral ramp schematically ..... 119
A.3.2 Spiral ramp - cross-section ..... 119
A.3.3 Spiral ramp - calculation ..... 119
A.7.1 Available area for levering on side of the pyramid ..... 120
A.8.1 Force diagram ..... 120
A.8.2 Number of blocks arriving per unit time ..... 120
A.8.3 Stepwise displacement by levering ..... 120
Author Index ..... 121
Subject Index ..... 122
List of symbols and units used ..... 124
Tables in text
4.1 Hauling experiment ..... 19
6.1 Total workforce for the various building methods ..... 29
7.1 Results for the combination method ..... 37
7.2 Exterior ramp, base case - Workforce by activity vs height ..... 41
7.3 Interior ramp, base case - Workforce by activity vs height ..... 41
8.1 Numerical values for the for the levering method - Volume equations ..... 47
8.2 Numerical values for the for the levering method - Manpower equations ..... 48
12.1 Layer thickness of Sphinx and Pyramid ..... 55
13.1 Literature review ..... 61
13.2 Workforce corresponding with pyramid building in series ..... 66
13.3 Comparison with Romer's workforce numbers ..... 69
13.4 Matching Romer's volume curve ..... 69
13.5 Characteristics of some model curves ..... 71
13.6 Stone production ..... 72
Tables in Appendices
4-1 Volume equations for pyramid, casing and ramps ..... 88
4-2 Manpower equations for the various activities ..... 91
9-1 Calculations for mini-pyramid ..... 110

## Figures in text

1.1 Map of ancient Egypt ..... X
1.2 The Cheops pyramid ..... 1
2.1 Project schedule of the pyramid construction ..... 2
2.2 Exterior and interior linear ramp ..... 3
2.3 Spiral ramp ..... 3
2.4 Material flow ..... 4
3.1 Calculation of volume linear ramp ..... 6
3.2 Cross-section of linear ramp for successive stages ..... 6
3.3 Ratio of ramp/pyramid volumes vs relative height ..... 6
3.4 Ratio of interior/exterior ramp volumes vs relative total height ..... 6
4.1 Giza plateau with possible orientation of linear ramp ..... 9
4.2 Quarrying limestone ..... 10
4.3 North face of Meidum pyramid showing undressed inner stones ..... 11
4.4 Unfinished obelisk at Aswan ..... 12
4.5 Granite quarrying squatting ..... 12
4.6 Granite quarrying standing ..... 12
4.7 Transport of Djehutihotep monument ..... 16
4.8 Hauling a block up the ramp ..... 17
4.9 Levering ..... 24
5.1 Calculation of the average horizontal distance ..... 27
5.2 Total manpower versus fraction of pyramid completed ..... 28
5.3 Fractional manpower for the various activities ..... 28
6.1 Calculation scheme ..... 30
6.2 Fraction of pyramid completed versus time ..... 30
6.3 Block travel time ..... 30
6.4 Effective building rate versus fraction of pyramid completed ..... 31
6.5 Adjusted building rate versus fraction of pyramid completed ..... 31
6.6 Simultaneous ramp and pyramid building ..... 32
6.7 Number of builders as a fraction of total workforce, vs fraction of pyramid completed ..... 33
6.8 Workforce vs time for exterior ramp of 133 m ..... 34
6.9 Workforce vs time for spiral ramp of 133 m ..... 34
6.10 Workforce vs time for levering ..... 34
6.11 Shipping workforce versus fraction of pyramid completed ..... 33
7.1 Workforce vs time for exterior ramp of 82 m ..... 40
7.2 Workforce vs time for interior ramp of 82 m ..... 40
7.3 Workforce vs time for spiral ramp of 82 m ..... 40
7.4 Height of pyramid in cubits versus thickness layers in metres ..... 42
8.1 Area per hauling team ..... 44
8.2 Horizontal area per builder versus fraction of pyramid completed ..... 45
8.3 Inclined area per builder versus fraction of pyramid completed ..... 45
8.4 Minimum number of hauling trains vs time for linear ramp ..... 46
8.5 Minimum number of hauling trains vs time for spiral ramp ..... 46
11.1 Seagoing vessel dating from about 2500 B.C. ..... 51
11.2 H-shaped hoist ..... 51
11.3 Bearing stones of the fourth dynasty ..... 52
11.4 Placing the topmost layers ..... 52
12.1 Section of a nummulites limestone ..... 53
12.2 Detail of a nummulites limestone ..... 54
12.3 Chephren quarry showing the trenches around the removed building blocks ..... 54
12.4 Side view of the Sphinx showing the constant thickness of the layers ..... 55
12.5 The Sphinx prior to the extensive restoration ..... 56
12.6 Cross-section of the Mokattam formation ..... 60
12.7 Estimated contour map of the quarry area prior to the excavation ..... 57
12.8 Estimated contour map of the quarry area on completion of the excavation ..... 57
12.9 Thin section of Tura limestone ..... 60
13.1 Stone production for the construction of pyramids ..... 65
13.2 Matching Romer' building schedule ..... 70
13.3 Romer's building schedule vs model curves ..... 71
13.4 Effect of early start of quarrying on volume to be stored ..... 76
A.9.1 Mini-pyramid ..... 110
A.9.2 Workforce for mini-pyramid vs time in hours ..... 111

