Colosseum Project Walkthrough

Overview of project

The purpose of this project is to calculate the amount of land that would have been required to support the humans and oxen involved in building the Colosseum. We have broken the project down into three stages.

The first stage (pages 2 - 20 of this document) of the project involved determining the mass and volume of the components of a representative segment of the Colosseum.

The second stage (pages 21 - 39) of the project entailed determining the amount of human and animal energy that would have been required to construct this segment, including extracting, producing, transporting and assembling the various materials required.

The third stage (pages 39 - 43) of the project involved determining the amount of land that would have been necessary to produce the energy required to build the Colosseum.

Colosseum Project Walkthrough *continued...*

Stage One

If the Colosseum is conceived as a giant elliptical wheel, then its eighty radial walls can be conceived as spokes[1]. For the purposes of our calculations, one segment was taken to be the area bounded by two "spokes", plus the materials required for one of the radial walls. We have assumed that the each of the eighty segments that comprise the Colosseum was identical. This is not technically accurate, as there were special entranceways at the intersection of the major and minor axes and the façade that were different from the typical segment. However, for the purposes of the final amount of land required and given our other assumptions, we have judged that the differences between segments is not significant.

For the representative segment, we identified each of the component parts by level, and then proceeded to identify the dimensions and material of each component. A list of the components used in our calculations follows:

Table 1. Elements of Colosseum

Substructure
Outer retaining wall
Inner retaining wall
Foundation

Level 1
Floor
Radial
Pier 1
Pier 2
Pier 3
Pier 4
Pier 5
Pier 6
Pier 7
Pier 8
Wall 3-6, excluding piers
Wall 7-8, excluding piers
Vault, 3-6
Vault, 7-8
Circumferential
Façade
Springing to crown
Crown to ceiling
Arcade at Pier 2

Level 1 *continued...*
Springing to crown
Crown to ceiling
Arcade at Pier 3
Springing to crown
Crown to ceiling
Arcade at Pier 6
Springing to crown
Crown to ceiling
Arcade at Pier 7
Springing to crown
Crown to ceiling
Entablature at Pier 8
Arena wall
Vault, Ambulatory 1
Vault, Ambulatory 2
Vault, Ambulatory 3
Marble

Level 2
Floor
Radial
Pier 1
Pier 2
Pier 3
Pier 4
Pier 5
Pier 6
Wall, 3-6
Vault, 3-6
Circumferential
Façade
Springing to crown
Crown to ceiling
Arcade at Pier 2
Springing to crown
Crown to ceiling
Arcade at Pier 3
Springing to crown
Crown to ceiling
Vault, Ambulatory 1
Vault, Ambulatory 2b
Vault, Ambulatory 2a
Inner wall

Level 3
Floor
Radial
Pier 1
Pier 2
Pier 3
Circumferential
Façade
Springing to crown
Crown to ceiling
Arcade 1
Springing to crown
Crown to ceiling
Inner wall
Vault, Ambulatory 1a
Vault, Ambulatory 2
Vault, Ambulatory 1b

Level 4
Façade
Area of wall
Area of window
Pier 1
Inner column

[1] For diagrams that provide a visual overview of the Colosseum, see Taylor, Rabun, *Roman Builders: A Study in Architectural Process*, Cambridge: Cambridge University, 2003, pp. 133-173.

Colosseum Project Walkthrough *continued...*

We have made further simplifying assumptions with respect to our representative segment, which include:

a. The underground passageways below the arena were not built during the initial phase of construction.[2] The foundation below the ring area of the Colosseum was solid (e.g. did not have passageways built underneath it), and was made of concrete with a three metre-thick brick retaining wall on both the inner and outer edges of the ring.[3]

b. Stairways were not included in the calculations. This assumption was made on the basis that the ceiling area above any stairway would have been open space. We have assumed that the material required for a stairway would be roughly equal to the ceiling mass had the stairway not been built. The ceiling mass and stairway mass are thus assumed to cancel one another out. We recognize that there were circumferential staircases on the upper level,[4] but have omitted these from our calculations.

c. Doorways leading from level one into the arena, and from levels 2 and 3 into the respective seating tiers were not calculated.

d. We have not included columns, statues, or fountains in our calculations – with the exception of the columns on the inner ellipse of the fourth level.

e. Because we did not have a complete set of measurements for all elements of the Colosseum, some interpolation/extrapolation was required. Based on calculations of the difference between the façade wall ellipse and the arena wall ellipse, we have determined that the width of a segment wedge decreased by 8 cm for every metre distance from the façade wall. We have assumed that the cm decrease in width is equally distributed amongst all elements at a given distance from the perimeter (e.g. the cm decrease is distributed equally across the width of a walkway and the width of the piers; both the walkway and pier widths change).

Because many of the components were elliptical, arched or vaulted, several preliminary calculations had to be made before determining the overall dimensions of all component parts. The first of these involved determining the surface areas of the ellipses formed by the outer and inner retaining walls, the perimeter, the inner walls of levels one, two and three (the walls closest to the arena), and the ambulatories. For the purposes of the table below, "outer" refers to the ellipse closest to the perimeter/facade, while "inner" refers to the ellipse closest to the arena.

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[2] Taylor, *Roman Builders*, p. 136.

[3] Rea, Rossella, "*The Colosseum Through the Centuries*," in Coarelli, Filippo, et. al., *The Colosseum*, Los Angeles: J. Paul Getty Museum, 2001.

[4] Taylor, *Roman Builders*, p. 164.

Colosseum Project Walkthrough *continued...*

Table 2. Elliptical Surface Areas[5]

Ellipses	Major axis	Minor axis	a	b	Surface area (sq. m.)
			0.5 x major axis	0.5 x minor axis	pi x a x b
Perimeter	187.00	155.00	93.50	77.50	22,764.77
L1 Inner Ellipse	85.30	53.30	42.65	26.65	3,570.80
L2 Inner Ellipse	128.84	96.84	64.42	48.42	9,799.31
L3 Inner Ellipse	156.56	124.56	78.28	62.28	15,316.14
Outer retaining wall			96.50	80.50	24,404.68
Inner retaining wall			39.65	23.65	2,945.94
Outer ellipse of arena wall			43.66	27.66	3,793.90
Outer ellipse of ambulatory 1			91.14	75.14	21,514.44
Inner ellipse of ambulatory 1			86.26	70.26	19,040.02
Outer ellipse of ambulatory 2			84.41	68.41	18,141.09
Inner ellipse of ambulatory 2			80.03	64.03	16,098.53
ellipse of ambulatory 3			64.54	48.54	9,841.89
Inner ellipse of ambulatory 3			60.16	44.16	8,346.16
Outer ellipse of inner wall L2			65.55	49.55	10,203.90
Outer ellipse of inner wall L3			80.03	64.03	16,098.53

Having calculated the elliptical surface areas, it was now possible to calculate the “footprints” of the various elliptical rings that make up the floors and circumferential walls of the Colosseum.

Table 3. Irregular Footprints

Footprints	Surface area outer ellipse	Surface area inner ellipse	Surface area of outer - inner ellipse	Footprint of segment (1/80 total)
Outer retaining wall	24,404.68	22,764.77	1,639.91	20.50
Inner retaining wall	3,570.80	2,945.94	624.86	7.81
Foundation	22,764.77	3,570.80	19,193.96	239.92
Arena wall	3,793.90	3,570.80	223.09	2.79
Ambulatory 1	21,514.44	19,040.02	2,474.42	30.93
Ambulatory 2	18,141.09	16,098.53	2,042.56	25.53
Ambulatory 3	9,841.89	8,346.16	1,495.73	18.70
Level 2, Inner Wall	10,203.90	9,799.31	404.59	5.06
Level 3, Inner Wall	16,098.53	15,316.14	782.39	9.78

[5] Measurements of the various ellipses are based on conversion to metres of the cross-sectional scaled diagram in Rea, “The Colosseum Through the Centuries”. The scaling factor is derived from Taylor, Roman Builders, p. 142, in which the original scaled diagram is reproduced from Rea’s Italian article, “Recenti osservazioni sulla struttura dell’Anfiteatro Flavio,” in Reggiani, A.M., Anfiteatro Flavio: Immagine, Testimonianze, Spetta-Coli. Rome: Quasar, 1988. Vertical heights (used in later calculations) and circumferential widths are taken from Taylor, Roman Builders, p. 155, in which a diagram is reproduced from Wilson-Jones, M., Principles of Roman Architecture, New Haven: Yale University Press, 1999.

Colosseum Project Walkthrough *continued...*

For instance, the total surface area of the foundation, stretching from the perimeter to the arena in a donut-shape, is given by the surface area of the “perimeter” ellipse (22,767.77 m) minus the surface area of the level one “inner ellipse” (3,570.80 m). By dividing the total surface area of the foundation by 80, we obtain the footprint of a representative segment, which is equal to 239.92 m. Similarly, the footprint of the arena wall is given by the surface area of the “outer ellipse of arena wall” minus the surface area of “level one inner ellipse”. Dividing by 80, we obtain the footprint of the arena wall for the representative segment, equal to 2.79 m.

The elliptical calculations also allow us to determine the circumference of the perimeter and of the arena, 538.39 m and 220.59 m, respectively. Dividing by 80, we find the portion of the circumference that bounds our representative segment: 6.73 m on the perimeter side and 2.76 m on the arena side of the segment. These circumference calculations allow us to determine the change in segment width for each metre change in segment depth. We need to know this change in order to find the width of various components, according to assumption “e.” above.

Table 4. Circumferences of perimeter and arena

Ellipses	Major axis	Minor axis	a	b	Surface area (sq. m.)	Circumference	Circumference of segment
			0.5 x major axis	0.5 x minor axis	pi x a x b	pi[2(a^2 +b^2)-0.5(a-b)^2)]^(1/2)	(1/80 total)
Perimeter	187.00	155.00	93.50	77.50	22,764.77	538.39	6.73
L1 Inner Ellipse	85.30	53.30	42.65	26.65	3,570.80	220.59	2.76

Table 5. Change in width of representative segment

Change in width due to wedge shape	
Segment of circumference of outer wall	6.73
Segment of circumference of inner wall	2.76
Difference between segment lengths	3.97
Distance from outer to inner wall (L1)	50.85
Change in width per metre depth	0.08

The difference between the perimeter and arena bounding lengths is 3.97 m. The distance from the perimeter to the arena is 50.85 m[6], yielding an 8 cm change in wedge width per 1 m change in wedge depth (for every one metre we move from the perimeter to the arena, the width of the segment decreases by 8 cm).

In addition to finding the dimensions of important ellipses and footprints, preliminary calculations were required when calculating arches and vaults. We have made the following assumptions with respect to arches and vaults:

a. All arches were semi-circular, and therefore, the rise is equal to ½ the span in all instances. This is not accurate, but immensely simplified the calculations, as equations for a simple circle could be used in all instances, rather than having to calculate arc lengths and areas and elliptical segments.

b. All vaults – including annular, radial, and diagonal vaults – were barrel vaults. We recognize that this is not accurate, as both cross-vaults and “conical” vaults were used in construction.

[6] Ibid.

Colosseum Project Walkthrough *continued...*

Table 6. Preliminary arch measurements[7]

Arches	Height of Springing from floor	Rise	Span	Area of arch	Area of spandrel	Surface area of intrado
Level 1		r	2r	0.5 x pi x r^2	rise x span - area of arch	pi x r x depth of arch
Façade	4.95	2.22	4.44	7.74	2.12	16.46
Arcade at Pier 2	4.95	2.03	4.07	6.49	1.77	11.82
Arcade at Pier 3	4.95	1.87	3.75	5.51	1.51	9.88
Arcade at Pier 6	4.95	1.66	3.33	4.35	1.19	5.28
Arcade at Pier 7	4.95	1.66	3.33	4.35	1.19	5.28
Level 2	4.45					
Level 3	4.40					

The area of the arch, the area of the spandrel, and the surface area of the intrado will all be required in determining the volume and mass of the various arches in the representative segment.

The approach taken to determine the volume of the vaults was to calculate the total volume from springline to ceiling and then subtract the area of space that constitutes the archway. The height of the vault, springline to ceiling, was multiplied by the footprint of the ambulatory or the surface area of a radial corridor. In order to find the amount of “space” to subtract from this total volume, a ratio of the “space” to “solid” of the vault in cross-section was determined. To find this ratio, the area of the arch was divided by the area from springline to ceiling (height of the vault multiplied by the span of the vault). With the ratio determined, it is possible to subtract the amount of “space” from the total volume of the vault, yielding the solid portion of the vault: the total volume of the vault multiplied by (1 minus the ratio) yields the solid portion of the vault.

Additionally, the surface area of the intrado of the vaults was required for subsequent calculations. First the length of the intrado was determined, given by the pi times the rise of the arch. For circumferential vaults, the surface area of the inner ellipse of the ambulatory was subtracted from the ellipse formed by adding the length of the intrado to the minor and major axes of the inner ellipse of the ambulatory. For radial vaults, the length of the intrado was multiplied by the length of the radial corridor.

A table outlining our preliminary vault measurements can be found on the following pages.

[7] Ibid.

Colosseum Project Walkthrough *continued...*

Table 7. Preliminary vault measurements[8]

Vaults	**Footprint of ambulatory**	**Height of vault** (springline to ceiling)	**Width [span]**	**Rise**	**Volume from springline to ceiling** (footprint x height of vault or corridor depth x height x width)	**Area from springline to ceiling**	**Arch area**	**Ratio of arch area to springline-ceiling area**
Level 1							[pi x (0.5 x width)^2]/2	
Ambulatory 1	2,474.42	4.07	4.88	2.44	10,070.88	19.86	9.35	0.47
Ambulatory 2	2,042.56	4.07	4.38	2.19	8,313.22	17.83	7.53	0.42
Ambulatory 3	1,495.73	4.07	4.38	2.19	6,087.63	17.83	7.53	0.42
Radial 3-6		4.07	3.33	1.66	173.44	13.55	4.35	0.32
Radial 7-8		4.07	2.60	1.30	49.85	10.58	2.66	0.25
Level 2b								
Ambulatory 1	2,474.42	3.97	4.88	2.44	9,823.44	19.37	9.35	0.48
Ambulatory 2	2,042.56	3.97	4.38	2.19	8,108.97	17.39	7.53	0.43
Level 2a								
Ambulatory 2a	2,042.56	3.39	4.38	2.19	6,924.28	14.85	7.53	0.51
Radial 3-6		3.97	3.33	1.66	169.18	13.22	4.35	0.33
Level 3a								
Ambulatory 1a	2,474.42	3.40	4.88	2.44	8,413.02	16.59	9.35	0.56
Ambulatory 2	2,042.56	3.40	4.38	2.19	6,944.71	14.89	7.53	0.51
Level 3b								
Ambulatory 1b	2,474.42	3.46	4.88	2.44	8,561.49	16.88	9.35	0.55

[8] Ibid.

Colosseum Project Walkthrough *continued...*

Table 7. Preliminary vault measurements[8]

Vaults	**Total volume**	**Volume per segment**	**Length of intrado** (m) [= pi x r, where r = rise or 1/2 span]	**Surface area of intrado (sq. m)** [circumferential = pi*(a[inner ellipse] +pi*r)*(b[inner ellipse]+pi*r) -surface area of inner ellipse, [radial = corridor depth x pi()*r]	**Surface area of intrado per segment (sq. m)**
Level 1					
Ambulatory 1	5,328.98	66.61	7.67	3,953.89	49.42
Ambulatory 2	4,799.97	60.00	6.88	3,262.48	40.78
Ambulatory 3	,514.94	43.94	6.88	2,403.53	30.04
Radial 3-6	9,418.25	117.73	5.23	66.94	66.94
Radial 7-8	2,987.25	37.34	4.08	19.24	19.24
Level 2b					
Ambulatory 1	5,081.54	63.52	7.67	3,953.89	49.42
Ambulatory 2	4,595.72	57.45	6.88	3,262.48	40.78
Level 2a					
Ambulatory 2a	3,411.03	42.64	6.88	3,262.48	40.78
Radial 3-6	9,077.33	113.47	5.23	66.94	66.94
Level 3a					
Ambulatory 1a	3,671.12	45.89	7.67	3,953.89	49.42
Ambulatory 2	3,431.46	42.89	6.88	3,262.48	40.78
Level 3b					
Ambulatory 1b	3,819.58	47.74	7.67	3,953.89	49.42

[8] Ibid.

Colosseum Project Walkthrough *continued...*

Once we had determined these preliminary measures, it was possible to begin calculating the dimensions of the component parts of the segment. We obtained the following measures from scholarly sources and calculations based on these sources:

Table 8. Heights[9]

Heights of Levels	Floor to Ceiling
Level 1, Pier 1-7	12.40
Level 1, Pier 8	8.30
Level 1, Arena Wall	2.00
Level 2, Pier 1-3	11.80
Level 2, Pier 4	9.00
Level 2, Pier 5	6.10
Level 2, Pier 6	3.30
Level 2, Inner Wall	3.30
Level 3, Pier 1-2	13.30
Level 3, Pier 3	10.30
Level 3, Inner Wall	2.80
Level 4, Pier 1	11.47

Table 9. Depths of Piers and Walls[10]

Depths of Piers and Walls	
Depth of elliptical footprint, level 2	28.96
Depth of elliptical footprint, level 3	14.48
Depth of elliptical footprint, level 4	9.09
Width of façade piers	2.36
Depth of radial piers	
1	2.36
2	1.85
3	1.68
4 - 8	1.01
Arena wall	1.01
Depth of radial walls and ambulatories	
Piers 3-6	12.80
Less piers 4 and 5 (embedded)	2.02
Length filling wall P3-6 =	10.78
Piers 7-8	4.71
Distance between piers (width of ambulatories)	
1	4.88
2	4.38
3	4.38
4	3.37
Pier 8 to Arena Wall	9.77

Based on these measures and the preliminary calculations above, we were able to construct the table on the following page, indicating the volume of each of the component parts identified in Table 1, above.

[9] Ibid.

[10] Ibid.

Colosseum Project Walkthrough *continued...*

Table 10. Volume of elements in representative segment [11]

Element	Width [m]	Depth [m]	Surface Area [sq m]	Footprint [sq m]	Height [m]	Average height lifted [m]	Total volume [cu m]
							0.89
Excavation				268.23	11.00	5.50	2,950.58
Outer retaining wall		3.00		20.50	11.00	5.50	225.49
Inner retaining wall		3.00		7.81	11.00	5.50	85.92
Foundation				239.92	11.00	5.50	2,639.17
Level 1							
Floor				239.92	0.90	1.00	215.93
Radial							
Pier 1	2.36	2.36		5.57	12.40	6.20	69.06
Pier 2	2.16	1.85		4.00	12.40	6.20	49.59
Pier 3	1.99	1.68		3.34	12.40	6.20	41.48
Pier 4	1.77	1.01		1.79	12.40	6.20	22.16
Pier 5	1.77	1.01		1.79	12.40	6.20	22.16
Pier 6	1.77	1.01		1.79	12.40	6.20	22.16
Pier 7	1.77	1.01		1.79	12.40	6.20	22.16
Pier 8	1.38	1.01		1.40	8.30	4.15	11.59
Wall 3-6, excluding piers	1.77	10.78	133.67	19.08	12.40	6.20	236.55
Wall 7-8, excluding piers	1.38	4.71	48.75	6.51	10.35	5.18	67.38
Vault, 3-6	3.06	12.80			4.07	11.38	117.73
Vault, 7-8	2.17	4.71			4.07	11.38	37.34
Circumferential							
Façade							
Springing to crown	…	2.36	2.12			6.06	4.99
Crown to ceiling	4.44	2.36	23.22		5.23	9.79	54.80
Arcade at Pier 2							
Springing to crown	…	1.85	1.77			5.97	3.28
Crown to ceiling	4.07	1.85	22.03		5.42	9.69	40.75
Arcade at Pier 3							
Springing to crown	…	1.68	1.51			5.89	2.53
Crown to ceiling	3.75	1.68	20.89		5.58	9.61	35.10
Arcade at Pier 6							
Springing to crown	…	1.01	1.19			5.78	1.20
Crown to ceiling	3.33	1.01	19.26		5.79	9.51	19.45
Arcade at Pier 7							
Springing to crown	…	1.01	1.19			5.78	1.20
Crown to ceiling	3.33	1.01	19.26		5.79	9.51	19.45
Entablature at Pier 8	2.56	1.01	5.30		2.07	11.36	5.35
Arena wall	…	…	…	2.79	2.00	1.00	5.58

[11] Ibid.

Colosseum Project Walkthrough *continued...*

Table 10. Volume of elements in representative segment [11]

Element	Width [m]	Depth [m]	Surface Area [sq m]	Footprint [sq m]	Height [m]	Average height lifted [m]	Total volume [cu m]
Level 1							
Vault, Ambulatory 1					4.07	11.38	66.61
Vault, Ambulatory 2					4.07	11.38	60.00
Vault, Ambulatory 3					4.07	11.38	43.94
Marble					5.15	2.58	
Level 2							
Floor				119.66		12.40	17.71
Radial							
Pier 1	2.36	2.36		5.57	11.80	18.30	65.72
Pier 2	2.16	1.85		4.00	11.80	18.30	47.19
Pier 3	1.99	1.68		3.34	11.80	18.30	39.47
Pier 4	1.77	1.01		1.79	9.00	16.90	16.09
Pier 5	1.77	1.01		1.79	6.10	15.45	10.90
Pier 6	1.77	1.01		1.79	3.30	14.05	5.90
Wall, 3-6	1.77	10.78	81.39	19.08	7.55	16.18	144.03
Vault, 3-6		12.80			3.97	29.71	113.47
Circumferential							
Façade							
Springing to crown		2.36	2.12			17.96	4.99
Crown to ceiling	4.44	2.36	22.78		5.13	21.64	53.75
Arcade at Pier 2							
Springing to crown		1.85	1.77			17.87	3.28
Crown to ceiling	4.07	1.85	21.62		5.32	21.54	40.00
Arcade at Pier 3							
Springing to crown		1.68	1.51			17.79	2.53
Crown to ceiling	3.75	1.68	20.52		5.48	21.46	34.47
Vault, Ambulatory 1					3.97	14.71	63.52
Vault, Ambulatory 2b					3.97	23.21	57.45
Vault, Ambulatory 2a					3.39	21.08	42.64
Inner wall				5.06	3.30	14.05	16.69
Level 3							
Floor				70.41		24.20	10.42
Radial							
Pier 1	2.36	2.36		5.57	13.30	30.85	74.08
Pier 2	2.16	1.85		4.00	13.30	30.85	53.19
Pier 3	1.99	1.68		3.34	10.30	29.35	34.45
Circumferential							
Façade							

[11] Ibid.

Colosseum Project Walkthrough *continued...*

Table 10. Volume of elements in representative segment [11]

Element	Width [m]	Depth [m]	Surface Area [sq m]	Footprint [sq m]	Height [m]	Average height lifted [m]	Total volume [cu m]
Level 3							
Springing to crown		2.36	2.12			29.71	4.99
Crown to ceiling	4.44	2.36	29.66		6.68	34.16	70.00
Arcade 1							
Springing to crown		1.85	1.77			29.62	3.28
Crown to ceiling	4.07	1.85	27.93		6.87	32.57	51.66
Inner wall				9.78	2.80	25.60	27.38
Vault, Ambulatory 1a					3.40	31.20	45.89
Vault, Ambulatory 2					3.40	31.20	42.89
Vault, Ambulatory 1b					3.46	36.64	47.74
Level 4							
Façade							
Area of wall	4.44	2.36			11.47	43.24	120.19
Area of window	2.02	2.36			2.65	43.24	-6.32
Pier 1	2.36	2.36			11.47	43.24	63.88
Inner column	…	…	…	1.77	11.47	37.50	20.27

In the case of elliptical elements, such as floors and certain circumferential walls, the volume is given by the footprint (determined in preliminary steps) multiplied by the height of the element. In the case of rectangular elements, such as piers and radial walls, the volume is given by width by depth by height. For vaults, the volume is given by the preliminary vault calculations. For arches, the volume is given by the depth multiplied by the surface area determined in the preliminary arch calculations.

The area from “springline to crown” (spandrel) and “crown to ceiling” have been broken out as these are assumed to be made of different materials on upper levels. On upper levels, the actual arch itself was assumed to be made of travertine, while the area of above the arch to the ceiling was made of brick-faced concrete. It would have been more accurate to calculate the area from springline to the extrado of the arch, however, this would have greatly complicated matters and would not likely have resulted in significant changes to our overall numbers.

The average height lifted will be required for subsequent calculations, and is given as one half the height of the element plus the height of the floor on which it is found. In the case of arches, vaults and entablatures, it is given as one half the height of the element plus the height of the floor on which it is found, plus the height from floor to springline.

Once we had determined the total volume of each component, it was possible to calculate the mass by multiplying the total volume by the density of the material of the component.

[11] Ibid.

Colosseum Project Walkthrough *continued...*

The following densities of materials were used for calculations:[12]

a. Travertine 2,720 kg/cu m

b. Tufa 2,225 kg/cu m

c. Brick 2,403 kg/cu m

d. Pozzolano 1,602 kg/cu m

e. Lime 849 kg/cu m

f. Water 1,000 kg/cu m

g. Rubble 2,243 kg/cu m

h. Earth 1,442 kg/cu m

We have also assumed that Concrete was weight-bearing, and was used in all vaults, and in the floors and walls above level 1. Concrete was assumed to be half rubble and half mortar. Mortar was composed of water, lime, and pozzolano, in a respective ratio of 0.175 : 0.275 : 0.55. This corresponds to an average of 15-20% water, and one part lime to one part pozzolano.[13] The wet and dry mass are assumed to be the same (i.e. the water chemically bonds to the lime/pozzolano in the drying process rather than evaporating).

Based on the above numbers, we constructed the following table, indicating the mass of each of components of a representative segment of the Colosseum:

Table 11. Mass of elements in representative segment

Element	Total volume [cu m]	Material	Density of material [kg/cu m]	Mass of travertine, tufa, and brick (and earth and marble) [kg]
			kg per cubic metre	volume x density
Excavation	2,950.58	Earth	1,442.00	4,254,730.68
Outer retaining wall	225.49	Brick and mortar	2,403.00	441,869.75
Inner retaining wall	85.92	Brick and mortar	2,403.00	168,367.61
Foundation	2,639.17	Rubble and mortar	see rubble, lime, and pozzolano	…
Level 1				
Floor	215.93	Travertine	2,720.00	587,335.20
Radial				

12 Densities are based on values given by SiMetric, “Density of Bulk Materials,” available from: http://www.simetric.co.uk/si_materials.htm. Value for “dry sand” taken as proxy for pozzolano. Values for the density of travertine and tufa are based on information from contemporary stone wholesalers.

13 Adam, Jean-Pierre, *Roman Building: Materials and Techniques*, Translated by Anthony Mathews, London: B.T. Batsford, 1999, p. 74.

Colosseum Project Walkthrough *continued...*

Pier 1	69.06	Travertine	2,720.00	187,851.47
Pier 2	49.59	Travertine	2,720.00	134,880.72
Pier 3	41.48	Travertine	2,720.00	112,815.58
Pier 4	22.16	Travertine	2,720.00	60,283.27
Pier 5	22.16	Travertine	2,720.00	60,283.27
Pier 6	22.16	Travertine	2,720.00	60,283.27
Pier 7	22.16	Travertine	2,720.00	60,283.27
Pier 8	11.59	Travertine	2,720.00	31,515.19
Wall 3-6, excluding piers	236.55	Tufa	2,225.00	526,326.59
Wall 7-8, excluding piers	67.38	Tufa	2,225.00	149,914.24
Vault, 3-6	117.73	Rubble and Mortar	see rubble, lime, and pozzolano	…
Vault, 7-8	37.34	Rubble and Mortar	see rubble, lime, and pozzolano	…
Circumferential				
Façade				
Springing to crown	4.99	Travertine	2,720.00	13,578.45
Crown to ceiling	54.80	Travertine	2,720.00	149,061.53
Arcade at Pier 2				
Springing to crown	3.28	Travertine	2,720.00	8,930.20
Crown to ceiling	40.75	Travertine	2,720.00	110,846.96
Arcade at Pier 3				
Springing to crown	2.53	Travertine	2,720.00	6,879.58
Crown to ceiling	35.10	Travertine	2,720.00	95,461.50
Arcade at Pier 6				
Springing to crown	1.20	Travertine	2,720.00	3,267.42
Crown to ceiling	19.45	Travertine	2,720.00	52,914.52
Arcade at Pier 7				
Springing to crown	1.20	Travertine	2,720.00	3,267.42
Crown to ceiling	19.45	Travertine	2,720.00	52,914.52
Entablature at Pier 8	5.35	Travertine	2,720.00	14,556.23
Arena wall	5.58	Travertine	2,720.00	15,170.41
Vault, Ambulatory 1	66.61	Rubble and Mortar	see rubble, lime, and pozzolano	…
Vault, Ambulatory 2	60.00	Rubble and Mortar	see rubble, lime, and pozzolano	…
Vault, Ambulatory 3	43.94	Rubble and Mortar	see rubble, lime, and pozzolano	…
Marble		Marble		6,000,000.00
Level 2				
Floor	17.71	Brick and mortar	2,403.00	37,048.62
Radial				
Pier 1	65.72	Travertine	2,720.00	178,761.88
Pier 2	47.19	Travertine	2,720.00	128,354.23
Pier 3	39.47	Travertine	2,720.00	107,356.76
Pier 4	16.09	Travertine	2,720.00	43,753.99

Colosseum Project Walkthrough *continued...*

Level 2				
Pier 5	10.90	Travertine	2,720.00	29,655.48
Pier 6	5.90	Travertine	2,720.00	16,043.13
Wall, 3-6	144.03	Brick and mortar, rubble and mortar	2,403.00	25,199.62
Vault, 3-6	113.47	Rubble and Mortar	see rubble, lime, and pozzolano	…
Circumferential				
Façade				
Springing to crown	4.99	Travertine	2,720.00	13,578.45
Crown to ceiling	53.75	Travertine	2,720.00	146,211.40
Arcade at Pier 2				
Springing to crown	3.28	Travertine	2,720.00	8,930.20
Crown to ceiling	40.00	Brick and mortar, rubble and mortar	2,403.00	6,694.51
Arcade at Pier 3				
Springing to crown	2.53	Travertine	2,720.00	6,879.58
Crown to ceiling	34.47	Brick and mortar, rubble and mortar	2,403.00	6,352.15
Vault, Ambulatory 1	63.52	Rubble and Mortar	see rubble, lime, and pozzolano	…
Vault, Ambulatory 2b	57.45	Rubble and Mortar	see rubble, lime, and pozzolano	…
Vault, Ambulatory 2a	42.64	Rubble and Mortar	see rubble, lime, and pozzolano	…
Inner wall	16.69	Brick and mortar, rubble and mortar	2,403.00	4,640.51
Level 3				
Floor	10.42	Brick and mortar	2,403.00	21,801.68
Radial				
Pier 1	74.08	Travertine	2,720.00	201,485.85
Pier 2	53.19	Travertine	2,720.00	144,670.45
Pier 3	34.45	Travertine	2,720.00	93,709.71
Circumferential				
Façade				
Springing to crown	4.99	Travertine	2,720.00	13,578.45
Crown to ceiling	70.00	Travertine	2,720.00	190,388.34
Arcade 1				
Springing to crown	3.28	Brick and mortar, rubble and mortar	2,403.00	549.48
Crown to ceiling	51.66	Brick and mortar, rubble and mortar	2,403.00	8,646.23
Inner wall	27.38	Brick and mortar, rubble and mortar	2,403.00	4,919.54
Vault, Ambulatory 1a	45.89	Rubble and mortar	see rubble, lime, and pozzolano	…
Vault, Ambulatory 2	42.89	Rubble and mortar	see rubble, lime, and pozzolano	…
Vault, Ambulatory 1b	47.74	Rubble and mortar	see rubble, lime, and pozzolano	…

Colosseum Project Walkthrough *continued...*

Level 4				
Façade				
Area of wall	120.19	Travertine	2,720.00	326,909.31
Area of window	-6.32	Travertine	2,720.00	-17,180.99
Pier 1	63.88	Travertine	2,720.00	173,762.61
Inner column	20.27	Travertine	2,720.00	55,132.12

For components made of rubble and mortar and brick and mortar, the calculation of mass was somewhat more complex, as mortar was composed of lime, pozzolano, and water.

We have assumed that all the bricks used were half-bessales, except in the case of the floors, where it has been assumed that full bessales were used. The dimensions of the bessale were based on the lydium size of brick cited by Adam (pp. 61-62) and the tubuli size of brick cited by DeLaine (p. 116).[14] The dimensions are as follows:

Height: 9 cm
Depth: 14.80 cm
Length: 29.60 cm

We have further assumed that there was 1 cm of mortar laid between each brick, and that the length-wise side of the brick would be the side exposed.

We had to determine the volume of brick that would be needed to face on cubic metre of wall, and the corresponding quantity of mortar. We also had to determine the volume of brick and mortar that would be needed to build a solid brick wall (the inner and outer retaining walls were brick).[15]

[14] Adam, Roman Building, pp. 61-62 and DeLaine, Janet, *The Baths of Caracalla: A Study in the Design, Construction, and Economics of Large-Scale Building Projects in Imperial Rome*, Supplementary Series Number 5, Portsmouth: Journal of Roman Archaeology, 1997, p. 116.

[15] Rea, “The Colosseum Through the Centuries”.

Colosseum Project Walkthrough *continued...*

Table 12. Brick measurements

	Bessales	Half-bessale
Length (cm)	29.6	
Depth (cm)	14.8	
Height (cm)	9	
Volume (cu. Cm)	3,942.72	1,971.36
Volume (cu. M)	0.003943	0.001971
Number of pieces per sq. m, height (assuming 1 cm of mortar between each brick)	10	10
Number of pieces per sq. m, length (assuming 1 cm of mortar between each brick)	3.27	3.27
Number of pieces per sq. m, height x length (assuming 1 cm mortar between each brick)	32.68	32.68
Number of pieces per cu. m. (assuming 1 cm mortar between each brick)	206.83	…
Volume of brick for 1 sq. m. of wall, 1 brick deep (number of bricks per sq. m x volume of each brick)	0.13	0.06
Volume of mortar for 1 sq. m. of wall, 1 brick deep (volume of .148 cu. m less volume of brick)	0.02	0.08
Volume of brick for 1 cu. m. of wall (# of pieces/cu. m. x volume of each piece)	0.82	…
Volume of mortar for 1 cu. m. of wall (1 cu. M. - volume of brick/cu. m)	0.18	…

We found that roughly 33 full bessales bricks were necessary to face a square metre of wall, corresponding to 0.13 cubic metres of brick and 0.02 cubic metres of mortar. When half-bessales are used, 0.06 and 0.08 cubic metres of brick and mortar, respectively, were needed.

Based on these calculations it was possible to construct the following table, showing the volume and mass of rubble, brick and mortar, including quantities of pozzolano, lime and water.

Colosseum Project Walkthrough *continued...*

Table 13. Volumes and mass of bricks, rubble, and mortar (broken down by water, lime and pozzolano)

Element	Total volume [cu m]	Material	Density of material [kg/cu m]	Mass of travertine, tufa, and brick (and earth and marble) [kg]	Volume of brick (x2 for walls because brick facing on both sides of wall) [cu m]	Number of bricks	Volume of mortar for bricks [cu m]
			kg per cubic metre	volume x density	Based on calculations above, multiplied by appropriate surface area or volume.	Based on calculations above	Based on calculations above for brick component of walls.
Outer retaining wall	225.49	Brick and mortar	2,403.00	441,869.75	183.88	46,638.50	41.61
Inner retaining wall	85.92	Brick and mortar	2,403.00	168,367.61	70.07	17,770.88	15.85
Foundation	2,639.17	Rubble and mortar	see rubble, lime, and pozzolano	…	…	…	
Level 1							
Vault, 3-6	117.73	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, 7-8	37.34	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, Ambulatory 1	66.61	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, Ambulatory 2	60.00	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, Ambulatory 3	43.94	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Level 2							
Floor	17.71	Brick and mortar	2,403.00	37,048.62	15.42	3,910.41	2.29
Wall, 3-6	144.03	Brick and mortar, rubble and mortar	2,403.00	25,199.62	10.49	5,319.54	13.60
Vault, 3-6	113.47	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Crown to ceiling	40.00	Brick and mortar, rubble and mortar	2,403.00	6,694.51	2.79	1,413.18	3.61
Crown to ceiling	34.47	Brick and mortar, rubble and mortar	2,403.00	6,352.15	2.64	1,340.91	3.43
Vault, Ambulatory 1	63.52	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, Ambulatory 2b	57.45	Rubble and Mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, Ambulatory 2a	42.64	Rubble and Mortar	see rubble, lime, and pozzolano	…			
Inner wall	16.69	Brick and mortar, rubble and mortar	2,403.00	4,640.51	1.93	979.59	2.51
Level 3							
Floor	10.42	Brick and mortar	2,403.00	21,801.68	9.07	2,301.12	1.35
Springing to crown	3.28	Brick and mortar, rubble and mortar	2,403.00	549.48	0.23	115.99	0.30
Crown to ceiling	51.66	Brick and mortar, rubble and mortar	2,403.00	8,646.23	3.60	1,825.19	4.67
Inner wall	27.38	Brick and mortar, rubble and mortar	2,403.00	4,919.54	2.05	1,038.50	2.66
Vault, Ambulatory 1a	45.89	Rubble and mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, Ambulatory 2	42.89	Rubble and mortar	see rubble, lime, and pozzolano	…	…	…	
Vault, Ambulatory 1b	47.74	Rubble and mortar	see rubble, lime, and pozzolano	…	…	…	

Colosseum Project Walkthrough *continued...*

Volume of rubble [cu m]	Mass of rubble [kg]	Volume of mortar for concrete [cu m]	Volume of water for mortar [cu m]	Mass of water for mortar [kg]	Volume of lime [cu m]	Mass of lime [kg]	Volume of pozzolano [cu m]	Mass of pozzolano [kg]
For brick-faced walls = .5*(total v - v brick - v mortar for brick)	Density of modern concrete used as proxy for rubble = 2,243 kg/ cu. M	Concrete walls and foundations are assumed to be 1/2 rubble and 1/2 mortar	Volume of mortar x percentage equal to water (see above calculations)		Based on calculations above	density of lime = 849 kg/cu. M ; mass = density x volume	Based on calculations above	proxy of dry sand used for pozzolano density (1,602 kg/cu m)
			7.28	7,280.92	11.44	9,713.79	22.88	36,658.40
			2.77	2,774.28	4.36	3,701.29	8.72	13,968.12
1,319.58	2,959,828.73	1,319.58	230.93	230,927.34	362.89	308,090.06	725.77	1,162,686.18
58.86	132,032.14	58.86	10.30	10,301.21	16.19	13,743.29	32.38	51,865.14
18.67	41,877.54	18.67	3.27	3,267.31	5.13	4,359.05	10.27	16,450.43
33.31	74,705.62	33.31	5.83	5,828.57	9.16	7,776.15	18.32	29,346.02
30.00	67,289.61	30.00	5.25	5,249.97	8.25	7,004.21	16.50	26,432.85
21.97	49,275.00	21.97	3.84	3,844.46	6.04	5,129.06	12.08	19,356.31
…			0.40	401.07	0.63	535.08	1.26	2,019.32
59.97	134,510.53	59.97	12.88	12,875.35	20.23	17,177.56	40.47	64,825.56
56.73	127,252.83	56.73	9.93	9,928.33	15.60	13,245.81	31.20	49,987.73
16.80	37,682.58	16.80	3.57	3,572.49	5.61	4,766.21	11.23	17,986.96
14.20	31,844.01	14.20	3.08	3,084.61	4.85	4,115.32	9.69	15,530.59
31.76	71,236.80	31.76	5.56	5,557.93	8.73	7,415.07	17.47	27,983.39
28.72	64,426.20	28.72	5.03	5,026.56	7.90	6,706.16	15.80	25,308.03
21.32	47,818.39	21.32	3.73	3,730.82	5.86	4,977.44	11.73	18,784.12
6.13	13,741.85	6.13	1.51	1,510.57	2.37	2,015.31	4.75	7,605.48
…			0.24	236.01	0.37	314.87	0.74	1,188.29
1.38	3,092.93	1.38	0.29	293.22	0.46	391.20	0.92	1,476.35
21.70	48,668.60	21.70	4.61	4,614.01	7.25	6,155.75	14.50	23,230.91
11.34	25,436.19	11.34	2.45	2,449.33	3.85	3,267.75	7.70	12,332.01
22.94	51,464.49	22.94	4.02	4,015.29	6.31	5,356.96	12.62	20,216.39
21.45	48,104.73	21.45	3.75	3,753.16	5.90	5,007.25	11.80	18,896.60
23.87	53,545.79	23.87	4.18	4,177.67	6.56	5,573.61	13.13	21,033.97

Colosseum Project Walkthrough *continued...*

Having established the dimensions, volume and mass of each of the components of a representative segment of the Colosseum, we arrived at the following summary measures:

Table 14. Total volume and mass of Colosseum by material

	Volumes	**Mass**			
	Per Segment	Entire Colosseum	Per Segment [kg]	Entire Colosseum [kg]	Entire Colosseum [metric tons]
Travertine	1,354.54	108,363.56	3,684,360.97	294,748,877.37	294,748.88
Tufa	303.93	24,314.28	676,240.83	54,099,266.34	54,099.27
Brick	302.16	24,172.77	726,089.69	58,087,174.83	58,087.17
Mortar	1,912.57	153,005.94	2,466,407.88	197,312,630.79	197,312.63
Lime	525.96	42,076.63	446,538.26	35,723,061.07	35,723.06
Pozzolano	1,051.92	84,153.27	1,685,169.14	134,813,530.81	134,813.53
Water	334.70	26,776.04	334,700.49	26,776,038.92	26,776.04
Rubble	1,820.70	145,656.16	4,083,834.57	326,706,765.81	326,706.77
Earth	2,950.58	236,046.09	4,254,730.68	340,378,454.79	340,378.45
Concrete	3,641.40	291,312.32	8,167,669.15	653,413,531.62	653,413.53
Above-ground concrete	1,002.23	80,178.75	2,248,011.69	179,840,935.07	179,840.94
	5,693.91	**455,512.70**	**11,636,933.94**	**930,954,715.15**	**930,954.72**

Table. 15 Percent volume and mass of Colosseum by material

	% Volume by material	**% Mass by Material**
Travertine	0.24	0.32
Tufa	0.05	0.06
Brick	0.05	0.06
Mortar	0.34	0.21
Lime	0.09	0.04
Pozzolano	0.18	0.14
Water	0.06	0.03
Rubble	0.32	0.35
Earth	0.52	
Concrete	0.64	
Above-ground concrete	0.18	
	1.00	**1.00**

“Concrete” and “Above-ground concrete” are not counted towards the final totals, as “concrete” is a summary measure comprised of rubble and mortar. It is included for illustrative purposes only.

Colosseum Project Walkthrough *continued...*

Stage Two

Having completed stage one, it was now possible to move on to the task of determining how much energy was required to extract, produce, transport, assemble and construct the various elements included in our model.

We used two approaches to calculate the required energy. The first, which we've called the "physical" approach, uses physics equations to determine the amount of joules required to lift and transport various materials. The second approach uses labour constant equations developed by DeLaine for estimating the energetic requirement of work that didn't easily lend itself to the "physical" approach.[16]

For the physical approach, we've used two equations: one for lifting, and one for transporting materials. The work required for lifting (in joules) is given by the equation:

mass of component (kg) x gravitational constant (9.8) x average height lifted (m)

The work required for transporting materials over land is given by the equation:

Frictional co-efficient (0.1) x mass of component (kg) x gravitational constant (9.8) x distance (m)

This formula calculates work for a mass being pulled or pushed continuously across a flat, level surface (e.g. no hills, no stopping and starting). In fact, the materials being transported would have been on carts with wheels, which would likely make the work easier. To account for this, we have chosen a low frictional coefficient (0.1). We recognize that the area between Tivoli and Rome is not devoid of hills, but assume that inclines and declines in the geography roughly cancel one another out.

As the second equation requires distances over which materials were transported, we've made the following assumptions:

a. Travertine: transported from the quarries at Tivoli (Tibur) to Rome, approximately 30 km. [17]
b. Tufa: abundant throughout Italy, and probably transported about 1 km.
c. Brick: Transported from within a range of 1 km.
d. Pozzolano: available within 3 km of Rome
e. Lime: transported from the vicinity of Tivoli, 30 km assumed
f. Water: Transported 300 m
g. Rubble: much concrete would probably have been recovered from Nero's destroyed complex. We have assumed a 1 km transport range for concrete.
h. Marble: Would have been transported over water for the bulk of its journey. Work involved in transport over water not included in calculations. Assume 1 km transport over land, to Rome, from port.
i. Earth: would have to be moved 500 m from site of excavation

[16] DeLaine, *The Baths of Caracalla*, pp. 268-269.

[17] Pearson, John, *Arena: The Story of the Colosseum*, London: Thames and Hudson, 1973., pp. 84-85.

Colosseum Project Walkthrough *continued...*

The physical work would have been carried out by both humans and oxen. We have assumed that all lifting work was done by humans, and all transportation over land was done by oxen, with two oxen per cart.[18] We have assumed the journey to the Colosseum would have taken twice as long as the return journey to the quarry or production site, and that the Tivoli to Rome would take the oxen 2 days to traverse with a heavy load.[19] As such, in order to have a steady stream of materials flowing daily to the construction site, there would have to have been 3 teams of oxen. **For every one team of oxen arriving at the Colosseum, there would have been two teams in transit, either in the process of bringing materials or making the return journey.** We have assumed one driver per cart, meaning that the number drivers would have been equal to the number of oxen teams. We have assumed a constant rate of movement for the oxen.

We have assumed that movement of materials around the site was carried out by humans. Additionally In order to approximate the work required to move materials around the construction site we have assumed there were 4 equidistant drop off points for materials coming in from outside. We have further assumed that materials were dropped at the drop point closest to the area where the work was to be done. Using this rationale, no onsite material would have to be moved more than one-quarter of the circumference of the outer ellipse of the Colosseum. Further, no onsite material would have to be moved more than one-half the radial depth of the Colosseum. We have used a higher frictional coefficient for (0.3) for horizontal movement around the Colosseum, assuming that much of the material would have been moved by humans, likely using logs as rolling devices, rather than pulled by ox cart.

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[18] DeLaine, *The Baths of Caracalla*, p. 98.

[19] Based on the speed of 1.67 km/hr for a heavily loaded cart, as given in DeLaine, ibid.

Colosseum Project Walkthrough *continued...*

Table 16. Human work: "physical approach"

Element	Lift travertine, tufa and brick [joules]	Translate travertine, tufa and brick onsite [joules]	Lift rubble [joules]	Translate rubble onsite [joules]	Carry water [joules]	Lift water [joules]	Translate lime onsite [joules]	Lift lime [joules]	Translate pozzolano onsite [joules]	Lift pozzolano [joules]
	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	Assumption: water source 300 m away; mass x 9.8 x 0.3 x distance	= mass x 9.8 x height	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	= mass x 9.8 x height
Excavation	229,329,983.92	1,178,631,331.48								
Outer retaining wall	23,816,779.30	122,405,286.14			6,421,773.70	392,441.73	2,690,882.00	523,573.33	10,154,989.32	1,975,888.03
Inner retaining wall	9,075,014.18	46,640,634.89			2,446,917.22	149,533.83	1,025,318.83	199,499.49	3,869,401.10	752,881.47
Foundation			159,534,768.46	819,921,901.87	203,677,915.40	12,446,983.72	85,346,083.83	16,606,054.42	322,083,454.19	62,668,784.88
Level 1										
Floor	5,755,884.99	162,701,642.75	…							
Radial										
Pier 1	11,413,855.24	52,037,988.58	…							
Pier 2	8,195,352.53	37,364,207.98	…							
Pier 3	6,854,674.49	31,251,795.77	…							
Pier 4	3,662,811.56	16,699,471.13	…							
Pier 5	3,662,811.56	16,699,471.13								
Pier 6	3,662,811.56									
Pier 7	3,662,811.56									
Pier 8	1,281,722.95	8,730,234.23	…							
Wall 3-6, excluding piers	31,979,603.48	145,801,239.38	…							
Wall 7-8, excluding piers	7,602,900.75	41,528,744.12	…							
Vault, 3-6	…		14,727,986.85	36,575,103.14	9,085,671.14	1,149,085.02	3,807,120.91	1,533,043.57	14,367,509.31	5,785,478.92
Vault, 7-8	…		4,671,377.15	11,600,777.67	2,881,764.97	364,463.22	1,207,530.79	486,246.00	4,557,042.00	1,835,020.24
Circumferential										
Façade										
Springing to crown	806,397.15	3,761,457.79	…							
Crown to ceiling	14,293,957.01	41,292,528.03	…							
Arcade at Pier 2										
Springing to crown	522,182.57	2,473,813.90								

Colosseum Project Walkthrough *continued...*

Table 16. Human work: "physical approach"

Element	Lift travertine, tufa and brick [joules]	Translate travertine, tufa and brick onsite [joules]	Lift rubble [joules]	Translate rubble onsite [joules]	Carry water [joules]	Lift water [joules]	Translate lime onsite [joules]	Lift lime [joules]	Translate pozzolano onsite [joules]	Lift pozzolano [joules]
	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	Assumption: water source 300 m away; mass x 9.8 x 0.3 x distance	= mass x 9.8 x height	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	= mass x 9.8 x height
Level 1										
Crown to ceiling	10,528,110.04	30,706,455.29								
Arcade at Pier 3										
Springing to crown	396,863.17	1,905,758.50								
Crown to ceiling	8,991,721.04	26,444,427.83								
Arcade at Pier 6										
Springing to crown	185,154.53	905,130.61								
Crown to ceiling	4,930,143.60	14,658,205.54								
Arcade at Pier 7										
Springing to crown	185,154.53	905,130.61								
Crown to ceiling	4,930,143.60	14,658,205.54								
Entablature at Pier 8	1,621,200.98	4,032,318.82								
Arena wall	148,670.00	4,202,455.89								
Vault, Ambulatory 1			8,333,300.38	20,694,703.49	5,140,799.46	650,168.33	2,154,122.11	867,417.44	8,129,337.16	3,273,504.67
Vault, Ambulatory 2			7,506,055.22	18,640,344.17	4,630,473.26	585,626.24	1,940,282.82	781,309.07	7,322,339.39	2,948,544.47
Vault, Ambulatory 3			5,496,552.16	13,649,996.03	3,390,814.09	428,843.79	1,420,834.96	572,138.88	5,362,020.29	2,159,167.23
Marble	151,410,000.00	1,662,100,027.60								
Level 2										
Floor	4,502,148.15	10,263,085.04			353,741.37	48,737.70	148,226.38	65,023.05	559,384.37	245,387.35
Radial										
Pier 1	32,059,155.85	49,520,021.39								

Colosseum Project Walkthrough *continued...*

Table 16. Human work: “physical approach”

Table 16. Human work: “physical approach”

Element	Lift travertine, tufa and brick [joules]	Translate travertine, tufa and brick onsite [joules]	Lift rubble [joules]	Translate rubble onsite [joules]	Carry water [joules]	Lift water [joules]	Translate lime onsite [joules]	Lift lime [joules]	Translate pozzolano onsite [joules]	Lift pozzolano [joules]
	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	Assumption: water source 300 m away; mass x 9.8 x 0.3 x distance	= mass x 9.8 x height	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	= mass x 9.8 x height
Level 2										
Pier 4	7,246,535.36	12,120,583.89								
Pier 5	4,490,136.26	8,215,062.41								
Pier 6	2,208,978.38	4,444,214.09								
Wall, 3-6	3,994,517.77	6,980,714.86	21,321,937.34	37,261,660.46	11,356,060.58	2,040,936.44	4,758,470.24	2,722,900.78	17,957,760.46	10,275,823.43
Vault, 3-6			37,047,561.41	35,251,155.02	8,756,787.39	2,890,469.57	3,669,310.48	3,856,299.33	13,847,433.21	14,553,101.36
Circumferential										
Façade										
Springing to crown	2,389,916.31	3,761,457.79								
Crown to ceiling	31,000,180.14	40,502,995.95								
Arcade at Pier 2										
Springing to crown	1,563,622.33	2,473,813.90								
Crown to ceiling	1,413,269.30	1,854,490.08	7,955,123.72	10,438,702.63	3,150,934.04	754,183.53	1,320,319.29	1,006,188.57	4,982,689.05	3,797,206.34
Arcade at Pier 3										
Springing to crown	1,199,159.85	1,905,758.50								
Crown to ceiling	1,335,997.28	1,759,650.98	6,697,499.04	8,821,320.93	2,720,629.88	648,762.62	1,140,011.20	865,542.02	4,302,233.10	3,266,427.13
Vault, Ambulatory 1			10,267,609.13	19,733,780.86	4,902,095.36	801,084.08	2,054,099.19	1,068,760.61	7,751,865.50	4,033,343.92
Vault, Ambulatory 2b			14,652,675.46	17,847,130.62	4,433,430.00	1,143,209.19	1,857,716.82	1,525,204.37	7,010,747.56	5,755,894.94
Vault, Ambulatory 2a			9,877,343.31	13,246,492.01	3,290,579.11	770,635.35	1,378,834.03	1,028,137.64	5,203,514.98	3,880,038.87
Inner wall	638,951.36		1,892,115.48	3,806,721.86	1,332,318.36	207,989.70	558,274.34	277,487.97	2,106,844.51	1,047,198.42
Level 3										
Floor	5,170,485.85	6,039,428.15			208,163.10	55,972.74	87,225.49	74,675.64	329,176.04	281,814.77
Radial										
Pier 1	60,915,216.91	55,814,939.36								

Colosseum Project Walkthrough *continued...*

Table 16. Human work: “physical approach”

Table 16. Human work: “physical approach”

Element	Lift travertine, tufa and brick [joules]	Translate travertine, tufa and brick onsite [joules]	Lift rubble [joules]	Translate rubble onsite [joules]	Carry water [joules]	Lift water [joules]	Translate lime onsite [joules]	Lift lime [joules]	Translate pozzolano onsite [joules]	Lift pozzolano [joules]
	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x average height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	Assumption: water source 300 m away; mass x 9.8 x 0.3 x distance	= mass x 9.8 x height	Onsite: [= 0.3 x mass x 9.8 x 94.22]	[= mass x 9.8 x height]	Onsite: [= 0.3 x mass x 9.8 x 94.22]	= mass x 9.8 x height
Level 3										
Pier 2	43,738,216.94	40,076,126.30								
Pier 3	26,953,724.93	25,959,152.94								
Circumferential										
Façade										
Springing to crown	3,953,475.15	3,761,457.79								
Crown to ceiling	63,735,922.68	52,740,743.26								
Arcade 1										
Springing to crown	159,482.01	152,214.03	897,705.15	856,794.53	258,624.38	85,106.71	108,370.01	113,544.51	408,972.35	428,500.15
Crown to ceiling	2,759,477.58	2,395,150.29	15,532,768.96	13,482,014.23	4,069,561.04	1,472,580.31	1,705,246.72	1,964,632.50	6,435,348.05	7,414,231.49
Inner wall	1,234,215.04	1,362,795.53	6,381,431.74	7,046,249.12	2,160,305.38	614,486.86	905,221.38	819,813.26	3,416,171.15	3,093,853.58
Vault, Ambulatory 1a			15,735,782.63	14,256,521.86	3,541,481.99	1,227,713.76	1,483,968.54	1,637,945.54	5,600,277.04	6,181,363.39
Vault, Ambulatory 2			14,708,503.55	13,325,813.36	3,310,283.43	1,147,564.92	1,387,090.63	1,531,015.54	5,234,674.17	5,777,825.45
Vault, Ambulatory 1b			19,224,168.78	14,833,075.44	3,684,704.45	1,499,879.42	1,543,982.29	2,001,053.41	5,826,760.04	7,551,678.60
Level 4										
Façade										
Area of wall	138,512,457.31	90,559,330.13								
Area of window	-7,279,636.50	-4,759,420.33								
Pier 1	73,623,738.57	48,135,139.44								
Inner column	20,261,055.44	15,272,517.37								
	1,118,959,525.94	**4,215,145,261.16**	**382,462,265.94**	**1,131,290,259.31**	**295,205,829.08**	**31,576,458.80**	**123,698,543.30**	**42,127,506.96**	**466,819,944.33**	**158,982,959.11**

Colosseum Project Walkthrough *continued...*

Table 17. Oxen work: "physical approach"

Element	Translate travertine, tufa and brick [joules]	Translate rubble [joules]	Translate lime [joules]	Translate pozzolano [joules]
	Offsite: [= 0.1 x mass x 9.8 x distance]	[=0.1*mass*9.8*1000]	lime came from Tivoli over land ; = mass x 9.8 x 0.1 x distance	pozzolano came from 3000 m away ; = mass x 9.8 x 0.1 x distance
Excavation	2,084,818,035.62			
Outer retaining wall	433,032,350.96		285,585,450.31	107,775,710.58
Inner retaining wall	165,000,257.87		108,817,904.34	41,066,262.13
Foundation		2,900,632,153.87	9,057,847,866.13	3,418,297,357.25
Level 1				
Floor	17,267,654,957.24	…		
Radial				
Pier 1	5,522,833,182.72	…		
Pier 2	3,965,493,157.70	…		
Pier 3	3,316,777,980.70	…		
Pier 4	1,772,328,174.36	…		
Pier 5				
Pier 6				
Pier 7				
Pier 8	926,546,713.13	…		
Wall 3-6, excluding piers	1,650,560,179.62	…		
Wall 7-8, excluding piers	470,131,060.95	…		
Vault, 3-6	…	129,391,494.44	404,052,775.27	152,483,520.85
Vault, 7-8		41,039,992.52	128,156,204.91	48,364,249.77
Circumferential				
Façade				
Springing to crown	399,206,511.41	…		
Crown to ceiling	4,382,408,894.98	…		
Arcade at Pier 2				
Springing to crown	262,547,839.95	…		
Crown to ceiling	3,258,900,560.96	…		
Arcade at Pier 3				
Springing to crown	202,259,667.85	…		
Crown to ceiling	2,806,568,191.87	…		
Arcade at Pier 6				
Springing to crown	96,062,232.91	…		
Crown to ceiling	1,555,687,031.39	…		
Arcade at Pier 7				
Springing to crown	96,062,232.91	…		
Crown to ceiling	1,555,687,031.39			
Entablature at Pier 8		…		

Colosseum Project Walkthrough *continued...*

Table 17. Oxen work: "physical approach"

Element	Translate travertine, tufa and brick [joules]	Translate rubble [joules]	Translate lime [joules]	Translate pozzolano [joules]
	Offsite: [= 0.1 x mass x 9.8 x distance]	[=0.1*mass*9.8*1000]	lime came from Tivoli over land ; = mass x 9.8 x 0.1 x distance	pozzolano came from 3000 m away ; = mass x 9.8 x 0.1 x distance
Level 1				
Arena wall	446,009,991.15	…		
Vault, Ambulatory 1		73,211,512.26	228,618,695.83	86,277,302.88
Vault, Ambulatory 2		65,943,819.20	205,923,760.86	77,712,571.24
Vault, Ambulatory 3		48,289,498.43	150,794,346.58	56,907,548.46
Marble	5,880,000,000.00			
Level 2				
Floor	36,307,646.39	…	15,731,383.94	5,936,790.83
Radial				
Pier 1	5,255,599,319.04	…		
Pier 2	3,773,614,456.52	…		
Pier 3	3,156,288,723.57	…		
Pier 4	1,286,367,223.33	…		
Pier 5	871,871,118.03	…		
Pier 6	471,667,981.89	…		
Wall, 3-6	24,695,627.65	131,820,323.61	505,020,236.81	190,587,142.37
Vault, 3-6		124,707,772.13	389,426,844.83	146,963,911.76
Circumferential				
Façade				
Springing to crown	399,206,511.41	…		
Crown to ceiling	4,298,615,225.86			
Arcade at Pier 2				
Springing to crown	262,547,839.95	…		
Crown to ceiling	6,560,616.97	36,928,927.55	140,126,537.96	52,881,675.81
Arcade at Pier 3				
Springing to crown	202,259,667.85	…		
Crown to ceiling	6,225,105.33	31,207,127.27	120,990,297.34	45,659,942.60
Vault, Ambulatory 1		69,812,062.78	218,003,183.55	82,271,166.09
Vault, Ambulatory 2b		63,137,672.99	197,160,965.68	74,405,622.39
Vault, Ambulatory 2a		46,862,024.97	146,336,753.64	55,225,319.04
Inner wall	4,547,696.50	13,467,014.11	59,250,100.62	22,360,108.64
Level 3				
Floor	21,365,644.02	…	9,257,310.31	3,493,571.52
Radial				
Pier 1	5,923,683,978.24	…		
Pier 2	4,253,311,209.47	…		

Colosseum Project Walkthrough *continued...*

Table 17. Oxen work: "physical approach"

Element	Translate travertine, tufa and brick [joules]	Translate rubble [joules]	Translate lime [joules]	Translate pozzolano [joules]
	Offsite: [= 0.1 x mass x 9.8 x distance]	[=0.1*mass*9.8*1000]	lime came from Tivoli over land ; = mass x 9.8 x 0.1 x distance	pozzolano came from 3000 m away ; = mass x 9.8 x 0.1 x distance
Level 3				
Pier 3	2,755,065,580.74	…		
Circumferential				
Façade				
Springing to crown	399,206,511.41	…		
Crown to ceiling	5,597,417,097.22	…		
Arcade 1				
Springing to crown	538,486.53	3,031,076.20	11,501,395.86	4,340,456.11
Crown to ceiling	8,473,306.93	47,695,230.35	180,979,193.02	68,298,861.53
Inner wall	4,821,152.50	24,927,467.75	96,071,866.45	36,256,096.59
Vault, Ambulatory 1a		50,435,200.73	157,494,763.57	59,436,186.39
Vault, Ambulatory 2		47,142,639.59	147,213,033.16	55,556,013.93
Vault, Ambulatory 1b		52,474,870.42	163,864,070.94	61,839,868.47
Level 4				
Façade				
Area of wall	9,611,133,848.06	…		
Area of window	-505,121,070.72	…		
Pier 1	5,108,620,694.02	…		
Inner column	1,620,884,434.93			
	113,372,351,871.29	**4,002,157,881.16**	**13,128,224,941.91**	**4,954,397,257.23**

For the physical approach, our total energy requirements summed as follows:

Table 18. Total human and oxen energy requirements: physical approach

	Per Segment	Entire Colosseum
Human joules	7,966,268,553.92	637,301,484,313.28
Ox joules	135,457,131,951.58	10,836,570,556,126.50

While the physical approach worked well for relatively straightforward movements such as lifting and pulling, more complex tasks such as erecting scaffolding and quarrying materials were not amenable to this approach. In order to estimate the energetic requirement of these types of tasks, we used the labour constants developed by DeLaine in her study of the baths of Caracalla. These equations yield the labour days required for various tasks based on the volume of material. Using these constants and our volume calculations, outlined above, we were able to calculate the labour days required for tasks associated with the various components.

A table of DeLaine's labour constants and our table applying these constants to the components of the Colosseum follow.

Colosseum Project Walkthrough *continued...*

Table 18. DeLaine Labour Constants[20]

	Skilled	**Unskilled**	**Supervision**	**Total** (Skilled plus unskilled plus supervision)
Quarry/produce travertine/tufa				0.887 d/cu m
Quarry/produce brick				5.17 d/1000 pieces
Quarry rubble (quarry pumice)				0.375 d/cu m
Produce lime				4.07 d/cu m
Quarry pozzolano				0.468 d/cu m
Shore foundations	.015 d/cu m	.015 d/cu m	0.1*skilled	2.1*(0.015 d/cu m)
Slake lime	1.2 d/cu m	...	0.1*unskilled	1.1*(1.2 d/cu m)
Lay foundations	0.35 + 0.01(d-1) d/cu m	...	0.1*unskilled	1.1*(0.35+0.01(d-1) d/cu m)
Lay brick and core for walls/floor	0.5*skilled	0.8hr/100 pieces+0.03(0.8hr/ 100 pieces)(height-1) +0.4/thickness of wall	0.1*skilled	1.6*[0.8 hours per 100 pieces *(0.97+0.03*(height)) +.4/thickness of wall]/12 = # Labour days
Mix mortar	0.7 d/cu m		0.1*unskilled	1.1*(0.7 d/cu m)
Erect scaffolding	2*skilled	0.021d/sq m face	0.1*skilled	3.1*(0.021 d /sq m face)
Prepare and erect centering	0.1 d/sq m	0.1 d/sq m	0.2*skilled	2.2*(0.1 d/sq m)
Load into baskets	0.06 d/cu m	...	0.1*unskilled	1.1*(0.06 d/cu m)
Lay vaults (lay foundation)	0.35 + 0.01(d-1) d/cu m	...	0.1*unskilled	1.1*(0.35+0.01(d-1) d/cu m)
Jimmy/adjust*				(1/6*cu m + 1/60*height)/12

* The Jimmy/adjust figure was invented by the author – it assumes this task took 10 minutes per cubic metre plus one minute for every metre increase in height.

[20] DeLaine, *The Baths of Caracalla*, pp. 268-269.

Colosseum Project Walkthrough *continued...*

Table 19. Tasks by segment element using DeLaine labour constants

Element	Quarry/ Produce travertine, tufa and brick [Labour days]	Quarry rubble [Labour days]	Excavate lime [Labour days]	Quarry pozzolano [Labour days]	Shoring foundations [Labour days]	Slaking Lime [Labour days]	Laying foundations [Labour days]	Lay brick and core for brick/ concrete walls; lay brick floor [Labour days]	Mix mortar [Labour days]	Erect scaffolding [Labour days]	Prepare and erect centering [Labour days]	Load into baskets [Labour days]	Lay vaults (laying foundation used as proxy as no data available in DeLaine on this one, depth is given by height of vault) [Labour days]	Jimmy, adjust stonework, check for level and plumb [Labour days]
	[tufa/ travertine = 0.887 Labour days/cu. M] , [brick = 5.17 Labour days/1000 pieces]	proxy of quarrying pumice used ; 0.375 Labour days /cu. M	[= 4.07 Labour days/ cu. m]	pozzolano took 0.468 Labour days per cu m to quarry	2.1*(0.015d/ cu.m)	(1.1)*1.2d/ cu m	1.1*(.35 +.01(height- 1)) d/cu.m	a work day is equal to 12 hours; 1.6*[0.8 hours per 100 pieces*(0.97+ 0.03*(height)) +.4/thickness of wall]/12 = # Labour days	1.1*(.7) d/cu.m	3.1*(.021 d/sq.m)	2.2*(.2 d/sq m intrado)	1.1*(.06 d/cu.m)	1.1*(0.35 +.01(depth - 1) d/cu m	10 minutes / cu m + 1 min/cu m for every m increase in height; = (1/6*cu m + 1/ 60*height)/12
Excavation	…											194.74		
Outer retaining wall	241.12		46.57	10.71		15.10		64.69	32.04			14.88		
Inner retaining wall	91.88		17.74	4.08		5.75		24.66	12.21			5.67		
Foundation		494.84	1,476.95	339.66	83.13	479.01	1,306.39		1,016.08			174.19		
Level 1														
Floor	191.53													3.00
Radial														
Pier 1	61.26													0.98
Pier 2	43.98													0.71
Pier 3	36.79													0.59
Pier 4	19.66													0.33
Pier 5	19.66													0.33
Pier 6														
Pier 7														
Pier 8	10.28													0.17
Wall 3-6, excluding piers	209.82									8.70				3.30
Wall 7-8, excluding piers	59.76									3.17				0.95
Vault, 3-6	…	22.07	65.88	15.15		21.37			45.33		29.45	7.77	49.30	
Vault, 7-8	…	7.00	20.90	4.81		6.78			14.38		8.46	2.46	15.64	
Circumferential														
Façade											7.24			

Colosseum Project Walkthrough *continued...*

Table 19. Tasks by segment element using DeLaine labour constants

Element	Quarry/ Produce travertine, tufa and brick [Labour days]	Quarry rubble [Labour days]	Excavate lime [Labour days]	Quarry pozzolano [Labour days]	Shoring foundations [Labour days]	Slaking Lime [Labour days]	Laying foundations [Labour days]	Lay brick and core for brick/ concrete walls; lay brick floor [Labour days]	Mix mortar [Labour days]	Erect scaffolding [Labour days]	Prepare and erect centering [Labour days]	Load into baskets [Labour days]	Lay vaults (laying foundation used as proxy as no data available in DeLaine on this one, depth is given by height of vault) [Labour days]	Jimmy, adjust stonework, check for level and plumb [Labour days]
	[tufa/ travertine = 0.887 Labour days/cu. M] , [brick = 5.17 Labour days/1000 pieces]	proxy of quarrying pumice used ; 0.375 Labour days /cu. M	[= 4.07 Labour days/ cu. m]	pozzolano took 0.468 Labour days per cu m to quarry	2.1*(0.015d/ cu.m)	(1.1)*1.2d/ cu m	1.1*(.35 +.01(height- 1)) d/cu.m	a work day is equal to 12 hours; 1.6*[0.8 hours per 100 pieces*(0.97+ 0.03*(height)) +.4/thickness of wall]/12 = # Labour days	1.1*(.7) d/cu.m	3.1*(.021 d/sq.m)	2.2*(.2 d/sq m intrado)	1.1*(.06 d/cu.m)	1.1*(0.35 +.01(depth - 1) d/cu m	10 minutes / cu m + 1 min/cu m for every m increase in height; = (1/6*cu m + 1/ 60*height)/12
Level 1														
Springing to crown	4.43													0.07
Crown to ceiling	48.61													0.77
Arcade at Pier 2											5.20			
Springing to crown	2.91													0.05
Crown to ceiling	36.15									1.43				0.57
Arcade at Pier 3											4.35			
Springing to crown	2.24													0.04
Crown to ceiling	31.13									1.36				0.50
Arcade at Pier 6											2.32			
Springing to crown	1.07													0.02
Crown to ceiling	17.26									1.25				0.28
Arcade at Pier 7											2.32			
Springing to crown	1.07													0.02
Crown to ceiling	17.26									1.25				0.28
Entablature at Pier 8										0.34				0.08
Arena wall	4.95													0.08

Colosseum Project Walkthrough *continued...*

Table 19. Tasks by segment element using DeLaine labour constants

Element	Quarry/ Produce travertine, tufa and brick [Labour days]	Quarry rubble [Labour days]	Excavate lime [Labour days]	Quarry pozzolano [Labour days]	Shoring foundations [Labour days]	Slaking Lime [Labour days]	Laying foundations [Labour days]	Lay brick and core for brick/ concrete walls; lay brick floor [Labour days]	Mix mortar [Labour days]	Erect scaffolding [Labour days]	Prepare and erect centering [Labour days]	Load into baskets [Labour days]	Lay vaults (laying foundation used as proxy as no data available in DeLaine on this one, depth is given by height of vault) [Labour days]	Jimmy, adjust stonework, check for level and plumb [Labour days]
	[tufa/ travertine = 0.887 Labour days/cu. M] , [brick = 5.17 Labour days/1000 pieces]	proxy of quarrying pumice used ; 0.375 Labour days /cu. M	[= 4.07 Labour days/ cu. m]	pozzolano took 0.468 Labour days per cu m to quarry	2.1*(0.015d/ cu.m)	(1.1)*1.2d/ cu m	1.1*(.35 +.01(height-1)) d/cu.m	a work day is equal to 12 hours; 1.6*[0.8 hours per 100 pieces*(0.97+ 0.03*(height)) +.4/thickness of wall]/12 = # Labour days	1.1*(.7) d/cu.m	3.1*(.021 d/sq.m)	2.2*(.2 d/sq m intrado)	1.1*(.06 d/cu.m)	1.1*(0.35 +.01(depth - 1) d/cu m	10 minutes / cu m + 1 min/cu m for every m increase in height; = (1/6*cu m + 1/ 60*height)/12
Level 1														
Vault, Ambulatory 1		12.49	37.28	8.57		12.09			25.65		21.75	4.40	2.63	
Vault, Ambulatory 2		11.25	33.58	7.72		10.89			23.10		17.94	3.96	2.41	
Vault, Ambulatory 3		8.24	24.59	5.65		7.97			16.92		13.22	2.90	1.87	
Marble														
Level 2														
Floor	20.22		2.57	0.59		0.83		4.20	1.76			1.17		
Radial														
Pier 1	58.29													0.93
Pier 2	41.86													0.67
Pier 3	35.01													0.56
Pier 4	14.27													0.24
Pier 5	9.67													0.16
Pier 6	5.23													0.09
Wall, 3-6	27.50	22.49	82.35	18.94		26.71		6.82	56.65	5.30		9.51		2.01
Vault, 3-6		21.27	63.50	14.60		20.59			43.68		29.45	7.49	4.09	
Circumferential														
Façade											7.24			
Springing to crown	4.43													0.07
Crown to ceiling	47.68													
Arcade at Pier 2											5.20			

Colosseum Project Walkthrough *continued...*

Table 19. Tasks by segment element using DeLaine labour constants

Element	Quarry/ Produce travertine, tufa and brick [Labour days]	Quarry rubble [Labour days]	Excavate lime [Labour days]	Quarry pozzolano [Labour days]	Shoring foundations [Labour days]	Slaking Lime [Labour days]	Laying foundations [Labour days]	Lay brick and core for brick/ concrete walls; lay brick floor [Labour days]	Mix mortar [Labour days]	Erect scaffolding [Labour days]	Prepare and erect centering [Labour days]	Load into baskets [Labour days]	Lay vaults (laying foundation used as proxy as no data available in DeLaine on this one, depth is given by height of vault) [Labour days]	Jimmy, adjust stonework, check for level and plumb [Labour days]
	[tufa/ travertine = 0.887 Labour days/cu. M] , [brick = 5.17 Labour days/1000 pieces]	proxy of quarrying pumice used ; 0.375 Labour days /cu. M	[= 4.07 Labour days/ cu. m]	pozzolano took 0.468 Labour days per cu m to quarry	2.1*(0.015d/ cu.m)	(1.1)*1.2d/ cu m	1.1*(.35 +.01(height- 1)) d/cu.m	a work day is equal to 12 hours; 1.6*[0.8 hours per 100 pieces*(0.97+ 0.03*(height)) +.4/thickness of wall]/12 = # Labour days	1.1*(.7) d/cu.m	3.1*(.021 d/sq.m)	2.2*(.2 d/sq m intrado)	1.1*(.06 d/cu.m)	1.1*(0.35 +.01(depth - 1) d/cu m	10 minutes / cu m + 1 min/cu m for every m increase in height; = (1/6*cu m + 1/ 60*height)/12
Level 2														
Springing to crown	2.91													0.05
Crown to ceiling	7.31	6.30	22.85	5.25		7.41		1.73	15.72	1.41		2.64		
Arcade at Pier 3											4.35			
Springing to crown	2.24													0.04
Crown to ceiling	6.93	5.32	19.73	4.54		6.40		1.65	13.57	1.34		2.27		
Vault, Ambulatory 1		11.91	35.55	8.17		11.53			24.45		21.75	4.19	2.46	
Vault, Ambulatory 2b		10.77	32.15	7.39		10.43			22.12		17.94	3.79	2.26	
Vault, Ambulatory 2a		7.99	23.86	5.49		7.74			16.42		17.94	2.81	1.51	
Inner wall	5.06	2.30	9.66	2.22		3.13		1.15	6.65	0.98		1.10		
Level 3														
Floor	11.90		1.51	0.35		0.49		2.49	1.04			0.69		
Radial														
Pier 1	65.71													1.05
Pier 2	47.18													0.76
Pier 3	30.56													0.49
Circumferential														
Façade											7.24			
Springing to crown	4.43													0.07

Colosseum Project Walkthrough *continued...*

Table 19. Tasks by segment element using DeLaine labour constants

Element	Quarry/ Produce travertine, tufa and brick [Labour days]	Quarry rubble [Labour days]	Excavate lime [Labour days]	Quarry pozzolano [Labour days]	Shoring foundations [Labour days]	Slaking Lime [Labour days]	Laying foundations [Labour days]	Lay brick and core for brick/ concrete walls; lay brick floor [Labour days]	Mix mortar [Labour days]	Erect scaffolding [Labour days]	Prepare and erect centering [Labour days]	Load into baskets [Labour days]	Lay vaults (laying foundation used as proxy as no data available in DeLaine on this one, depth is given by height of vault) [Labour days]	Jimmy, adjust stonework, check for level and plumb [Labour days]
	[tufa/ travertine = 0.887 Labour days/cu. M] , [brick = 5.17 Labour days/1000 pieces]	proxy of quarrying pumice used ; 0.375 Labour days /cu. M	[= 4.07 Labour days/ cu. m]	pozzolano took 0.468 Labour days per cu m to quarry	2.1*(0.015d/ cu.m)	(1.1)*1.2d/ cu m	1.1*(.35 +.01(height-1)) d/cu.m	a work day is equal to 12 hours; 1.6*[0.8 hours per 100 pieces*(0.97+ 0.03*(height)) +.4/thickness of wall]/12 = # Labour days	1.1*(.7) d/cu.m	3.1*(.021 d/sq.m)	2.2*(.2 d/sq m intrado)	1.1*(.06 d/cu.m)	1.1*(0.35 +.01(depth - 1) d/cu m	10 minutes / cu m + 1 min/cu m for every m increase in height; = (1/6*cu m + 1/ 60*height)/12
Level 3														
Crown to ceiling	62.09													0.98
Arcade 1											5.20			
Springing to crown	0.60	0.52	1.88	0.43		0.61		0.14	1.29			0.22		
Crown to ceiling	9.44	8.14	29.51	6.79		9.57		2.31	20.30	1.82		3.41		
Inner wall	5.37	4.25	15.67	3.60		5.08		1.22	10.78	1.03		1.81		
Vault, Ambulatory 1a		8.60	25.68	5.91		8.33			17.67		21.75	3.03	1.60	
Vault, Ambulatory 2		8.04	24.00	5.52		7.79			16.51		17.94	2.83	1.52	
Vault, Ambulatory 1b		8.95	26.72	6.14		8.67			18.38		21.75	3.15	1.68	
Level 4														
Façade														
Area of wall	106.61													1.69
Area of window	-5.60													-0.08
Pier 1	56.66													0.90
Inner column	17.98													0.30
	1,854.32	**682.76**	**2,140.65**	**492.30**	**83.13**	**694.26**	**1,306.39**	**111.06**	**1,472.68**	**29.39**	**290.02**	**461.08**	**86.96**	**24.04**

Colosseum Project Walkthrough *continued...*

Having arrived at the energy required for the "physical" approach and the labour days required under the DeLaine approach, we now had to begin translating these quantities into an overall energetic requirement for the total Colosseum in caloric terms. All joules were converted to calories using the ratio 1/4.1868. Calories were converted to kilocalories by dividing by 1000.

The joules yielded by the physical approach only include the energy required for carrying out a particular task, not the basal metabolic energy required to keep a worker or ox alive. The energy required to carry out such tasks is essentially "surplus" energy – the energy required above and beyond that necessary to keep the human or ox alive. We needed to determine the relationship between surplus energy and basal metabolic energy.

The standard equation for determining the basal metabolic rate of a mammal is given by:[21]

Basal metabolic requirement (kcal) = 70 x weight [kg] 0.75

For a 70 kg human, the basal metabolic rate is 1,694 kcal. This is the energy required to keep a resting human alive, without drawing on fat reserves.

Standard multipliers are also used to estimate an individual's caloric requirement based on physical activity level. For heavily and lightly active individuals, the basal metabolic requirement is multiplied by 1.78 and 1.55, respectively, to yield the total daily energetic requirement.[22] Therefore, a heavily active 70 kg human would require 3015 kcal per day, and a lightly active 70 kg human would require 2,626 kcal per day.

If muscles converted food energy directly into work energy, any one human could only contribute about 1300 kcal of surplus energy each day to the task of building the Colosseum. In order to produce 1300 kcal of surplus energy, a human would have to consume 1,300 kcal to translate into work in addition to 1,694 kcal for basal metabolic needs.

Muscles do not convert energy directly into work, however, as they are not perfectly efficient. Some energy is lost in the conversion from digested energy to hoisting, pulling, pushing and other physical activities performed by the muscle, much of it in the form of heat. For the purposes of this project, it was assumed that only 40% of the surplus calories would be available, the other 60% being lost as thermal energy and other energetic inefficiencies.

Given the basal metabolic needs of the workers and the fact that surplus food calories cannot be converted to work without a loss due to inefficiency, 4.71 kilocalories must be consumed for every calorie of physical work expended.

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[21] Smil, Vaclav "Laying Down the Law: Every Living Thing Obeys the Rules of Scaling Discovered by Max Kleibur," *Nature* v 403 (Feb 2000), 597.

[22] Smil, Vaclav, *Feeding the World*, Cambridge, Massachusetts: MIT Press, 2000, p. 223.

Colosseum Project Walkthrough *continued...*

We applied the same equations to oxen, assuming a 400 kg ox. The calculations are summarized in the table below.

Table 20. Physical activity level and surplus and basal metabolic energy requirements

Surplus, basal metabolic, and physical activity relationships		
	Human	Ox
weight [kg]	70.00	400.00
BMR = 70 x weight [kg] ^ 0.75	1,694.03	6,260.99
BMR kcal x 1.78 [PAL] = FTE kcal	3,015.38	11,144.56
BMR kcal x 1.55 [PAL] = FTE kcal LIGHT	2,625.75	9,704.54
Surplus kcal available / day = FTE kcal - BMR	1,321.34	4,883.57
Kcal available / day for work, given thermal loss of muscle (40%)	528.54	1,953.43
Additional kcal that must be consumed to support basal metabolic functions necessary to produce 1 kcal of surplus work	4.71	4.71

With these numbers, we could begin calculating the total energy required to feed the oxen involved in building the Colosseum. In addition to the “surplus” and basal metabolic calories, we also needed to know the energy expended by oxen making the return journey from the Colosseum to the site where construction materials were produced (e.g. the quarries in Tivoli for travertine).

We have assumed the journey to the Colosseum would have taken twice as long as the return journey to the quarry or production site, and that the Tivoli to Rome would take the oxen 2 days to traverse with a heavy load. As such, in order to have a steady stream of materials flowing daily to the construction site, there would have to have been 3 teams of oxen. For every one team of oxen arriving at the Colosseum, there would have been two teams in transit, either in the process of bringing materials or making the return journey. We have assumed one driver per cart, meaning that the number drivers would have been equal to the number of oxen teams. We have assumed a constant rate of movement for the oxen. We determined that approximately 1,200 oxen would be bringing materials to the Colosseum on any given day, while 600 would be making the return journey, for a total of 1,800 employed oxen.

Additionally, we had to find the amount of energy required to feed these oxen on their off-days. We have assumed that urban construction workers and transport oxen would have worked 220 out of 365 days. To find the off-day energetic requirement, we multiplied the total number of oxen by 145 days by 5 years by the daily “light” caloric requirement.

Colosseum Project Walkthrough *continued...*

Our calculations are outlined in the table below:

Table 21. Oxen caloric requirement

Oxen Caloric Requirement	Per segment	Entire Colosseum
Oxen energy requirement, before BMR and thermal loss, joules	135,457,131,951.58	10,836,570,556,126.50
Oxen energy requirement, before BMR and thermal loss, kcal	32,353,380.14	2,588,270,410.85
Basal Metabolic and thermal loss oxen energy requirement, kcal	152,226,801.41	12,178,144,112.57
Annual work to be carred out by oxen	6,470,676.03	517,654,082.17
Daily work to be carried out by oxen	29,412.16	2,352,973.10
Number of oxen required daily to bring materials	15.06	1,204.53
Number of oxen required daily to make return trip	7.53	602.27
Return journey oxen energy requirement	80,364,966.68	6,429,197,334.63
Total number oxen required per day	22.59	1,806.80
Off-day oxen energy requirement	158,903,456.85	12,712,276,548.02
Total Oxen Energy Requirement	**423,848,605.08**	**33,907,888,406.06**

For the human energetic requirement, we first had to translate the DeLaine labour days to their kilocaloric equivalent. We did this by multiplying the total number of labour days by 3,015 kcal, the daily caloric requirement of a heavily active 70 kg individual.

We also factored in an adjustment for inefficiency for the human labour. Our physical approach calculated the energy required to complete tasks assuming perfect efficiency. For instance, consider the task of excavating the foundation. If we draw an analogy between the earth to be excavated and a giant cake, our “physical” approach would be the equivalent of slicing the cake in one movement and lifting it out of the ground in one full piece. In reality, excavating the foundation would have been more like moving the “cake” spoonful by spoonful. We used a range of coefficients to account for human inefficiency, however, for the purposes of discussion at this point, we will illustrate our calculations using a 50% figure. Assuming 50% efficiency, the “surplus” energy requirement calculated in stage one would be doubled.

We also had to add the energy required to support the oxen cart drivers, of which there were approximately 900. As in the case of the oxen, we also calculated the caloric requirement to support all the workers on their off-days (number of workers x 145 days x 5 years x daily “light” caloric requirement).

Colosseum Project Walkthrough *continued...*

The summary table of our calculations of the human energy requirement follows:

Table 22. Human caloric requirement

Human Caloric Requirement	Per segment	Entire Colosseum
DeLaine Labour days	9,729.06	778,325.12
DeLaine human energy requirement, kcal	29,336,792.75	2,346,943,420.14
Annual DeLaine work to be carried out by humans	5,867,358.55	469,388,684.03
Daily DeLaine work to be carried out by humans	26,669.81	2,133,584.93
Number of DeLaine humans required per day	8.84	707.57
Human energy requirement, before BMR and thermal loss, joules	7,966,268,553.92	637,301,484,313.28
Human energy requirement, before BMR and thermal loss, kcal	1,902,710.56	152,216,844.44
Organizational inefficiency human energy requirement	1,902,710.56	152,216,844.44
Annual physical work to be carried out by humans	761,084.22	60,886,737.78
Daily physical work to be carried out by humans	3,459.47	276,757.90
Number of humans required per day for physical work	6.55	523.63
Basal metabolic and thermal loss human energy requirement, kcal	17,904,994.20	1,432,399,536.17
Number of drivers required per day	11.29	903.40
Driving oxen human energy requirement	32,616,440.56	2,609,315,244.42
Total number of humans required per day	26.68	2,134.60
Off-day human energy requirement	50,794,594.79	4,063,567,583.23
Total Human Energy Requirement	**134,458,243.41**	**10,756,659,472.84**

Stage Three

Having determined the total human and oxen energy requirements for building the Colosseum, we then turned to the task of finding how much land would have had to be under production to produce this much energy. In order to make this task tractable, we assumed that the entire energetic requirement was fulfilled by two foodstuffs: alfalfa hay in the case of oxen and wheat in the case of humans. We further assumed that the caloric content of these foods was the same in Roman times as it is today.

Several conversions from Roman to imperial to metric units will have to be made in the course of our calculations for this stage. We have included a conversion table here to facilitate our discussion below:

Table 23. Roman, imperial and metric unit conversions[23]

Conversion of measurements	Roman	Imperial	Metric
Modius --> Peck --> Litre	1.00	1.20	8.754
Iugerum --> Acre --> Hectare	1.00	0.62	0.252
Pound --> Ounces --> Kilogram	1.00	13.08	0.327

[23] M.C. Cato, *Cato the Censor, on Farming (De agricultura)*. Trans. Ernest Brehaut. New York: Octagon Books, Inc., 1966, p. xlvi.

Colosseum Project Walkthrough *continued...*

Taking the case of alfalfa first, we first had to establish caloric content of a metric ton of alfalfa hay. We found a modern figure indicating that, on average, a pound of alfalfa contains 1.16 megacalories, or 1,160 kilocalories.[24] Converting pounds to kilograms and then to metric tons, this figure corresponds to approximately 2,557,500 kcal per metric ton.

We now had to find out how many tons of dry alfalfa would be yielded by a hectare of farmland in Ancient Rome. Modern global alfalfa yields range from 5 to 75 metric tons of fresh matter per hectare per year. As Roman agricultural technology and methods would have been less advanced than those today, we estimated that yields would be in the lower range, at 15 tons per hectare annually. Alfalfa is approximately 83% water, so when dried, 15 tons of fresh alfalfa would correspond to 2.6 dry tons. In modern day Italy, dry matter alfalfa production ranges from 3 to 21 metric tons per hectare.[25] Our 2.6 figure falls just under the lower bound of modern day production.

With these two figures, we could now calculate the total caloric content of a hectare of alfalfa. Multiplying the dry matter yield by the caloric content of a ton of alfalfa, we found that the gross energy production per hectare was approximately 6,636,000 kcal per hectare.

However, we needed the surplus or net, rather than the gross, energetic content per hectare. The total 6.6 million kilocalories would not be available to feed Colosseum workers as much of this energy would be lost due to rot and vermin, some of it would be required to support the farm workers, and some would be used as seed for next year's harvest.

To find the amount of energy required to feed the farm workers, we needed to know how many labour days were required to farm a hectare of land and the average size of agricultural holding. M.S. Spurr has written a detailed analysis of the labour requirements of arable cultivation in Roman Italy. He has calculated that ten labour days would have been required to farm an iugerum of meadowland per year. Based on a conversion of roughly 4 iugerum to a hectare, approximately 40 labour days would have been required to farm a hectare of alfalfa. The caloric equivalent of 40 labour days is about 120,000 kcal (daily requirement of 3,015 kcal multiplied by 40 days).[26]

This number, however, only includes those calories expended by workers while they were actually farming. We also had to find how much energy would have been required to keep the workers alive during their off-days. To do this, we first needed to know how many workers would have been employed on an average holding. Columella states that a 200 iugerum, or 50 hectare, plot of land constituted an average agricultural landholding.[27] We assume here that the entire holding was dedicated to alfalfa production, which was unlikely to have been the case as multiple crops would generally have been cultivated on any given holding. However, the assumption is necessary for the purpose of calculation. Assuming an alfalfa monocrop, 2000 labour days would have been required annually to farm a 50 hectare holding (40 labour days per hectare multiplied by 50 hectares). Assuming a 300-day agricultural year, about 7 agricultural workers would have been required to fulfil this many labour days (2000 labour days per year divided by 300 working days is roughly 7). About 22,500 kcal would have been required to support these seven workers on their non-working days ("light" daily caloric requirement of 2,625 kcal by 65 days by 7 workers).

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[24] Consindine, Douglas M, ed. *Foods and Food Production Encyclopedia*. "Feedstuffs". p. 621.

[25] Purdue University, Centre for New Crops and Plants Products. "Medicago sativa L.: Yields and Economics". Based on James A. Duke, *Handbook of Enery Crops*, unpublished, 1983. Available from: http://www.hort.purdue.edu/newcrop/duke_energy/Medicago_sativa.html.

[26] Spurr, M.S. Arable Cultivation in Roman Italy, c.200 B.C. - c. A.D. 100. *Journal of Roman Sturdies Monographs* No. 3. London: Society for the Promotion of Roman Studies, 1986, p. 138-139.

[27] Columella recommends eight workers per 200 iugera arable land (Columella II, 12, 7) cited in A.H.M. Jones, *The Roman Economy: Studies in Ancient Economic and Administrative History* (Oxford, Basil Blackwell, 1974), p. 241.

Colosseum Project Walkthrough *continued...*

Our research indicated that in modern-day lower-income countries, agricultural loss due to rot and vermin is in the neighbourhood of 30%.[28] Using this 30% figure as a proxy, almost 2 million kcal would have been lost from the gross caloric output per hectare. Assuming that 10 percent of any crop would be used as seed in the next year, we subtracted a further 10%, or 664,000 kcal, from our gross output.

When all of these figures had been subtracted, the net energetic output per hectare of alfalfa farmland falls to 3,840,000 kcal. Our total oxen energy requirement from stage two was about 34 billion kcal over the five year building period, or 6.8 billion kcal per year. With a 6.8 billion annual energy requirement for feeding oxen, 1,766 hectares of farmland dedicated to alfalfa production would have been required. Because land was left fallow every other year, a further 1,766 hectares of land for alfalfa production would have been under fallow each year. In total, 3,532 ha, or 35.32 square km, would have to be dedicated to the production of alfalfa to feed the oxen involved in building the Colosseum.

A table summarizing our alfalfa calculations follows:

Table 24. Land requirement for alfalfa production

Caloric content, dry matter	
mcal/lb	1.16
kcal/lb	1,160.00
kcal/kg	2,557.34
kcal/MT	2,557,336.00
Yield/ha/year (MT)	
fresh matter	15.00
dry matter	2.60
Caloric content (kcal) per ha	6,636,286.92
Number of labour days per iugerum	10.00
Number of labour days per ha	39.68
Caloric equivalent of labour days / ha (kcal)	119,657.80
Size of holding, iugera	200.00
Size of holding, hectares	50.40
Labour days per holding	2,000.00
Labourers per holding	6.67
Caloric requirements for workers during off-days, per ha	22,575.89
Loss due to rot and spoilage (%)	30.00
30% loss in caloric terms	1,990,886.08
Seed for harvest in following year (%)	10.00
10% harvest in caloric terms	663,628.69
Surplus caloric content per ha	3,839,538.46
Total oxen energy requirement	33,907,888,406.06
Annual oxen energy requirement	6,781,577,681.21
Hectares to fulfill annual energy requirement	1,766.25
Hectares required under fallow	1,766.25
Total ha to fulfill annual energy requirement	3,532.50
Total sq. km to fulfill annual oxen energy requirement	**35.32**

[28] Smil Vaclav, *Feeding the World*. Cambridge, Massachusetts: MIT Press, 2000, pp. 182-188.

Colosseum Project Walkthrough *continued...*

For our wheat calculations, we had figures from Varro stating that wheat was sown at the rate of 5 pecks per *iugerum* and that annual yields in fertile regions such as Etruria could be as high as ten to one (volume of grain to volume of seed sown).[29] Five pecks per *iugerum* converts to 145 litres per hectare. Assuming a yield of 10:1, a hectare of land sown at this rate would yield 1,450 litres of wheat. With a wheat density of 800 kg per cubic metre, or 0.8 kg per litre, a hectare of wheat would therefore yield approximately 1,160 kg of wheat.[30] Modern wheat contains 342 kcal per 100 grams of edible portion, or 3,420 kcal per kilogram.[31] Multiplying 1,160 kg by 3,420 kcal/kg, we found that the gross annual energetic output of a hectare of wheat was about 4 million kilocalories.

As in the case of alfalfa, we had to subtract off the energy lost to rot and vermin, that used for seed, and the energy required to feed the farm labourers. Spurr has gauged that 14.5 labour days would have been required to farm an *iugerum* of wheat,[32] roughly 58 workers with an "on" day energetic requirement of 173,500 kcal. Using a 50 hectare holding size, again under the assumption that this land was dedicated solely to wheat production, this translates into 2,900 annual labour days, or about 10 workers per farm. Assuming 65 non-working days a year, these workers would have consumed 32,700 kcal during their "off" days.

With 30% of energetic output lost to rot and vermin, and 10% stored as seed for the following year, we further deducted 1,188,000 and 396,00 kcal, respectively, from the gross caloric output per hectare.

With these adjustments, we found that the surplus energy available from a hectare of land under wheat production was approximately 2,170,000 kcal. The total human energy requirement to build the Colosseum over all five years of construction was approximately 10.8 billion kilocalories, or 2.2 billion kcal per year. With a surplus output per hectare of 2.17 million kcal, 991 hectares under wheat production would have been required. A further 991 would have been left fallow on any given year, bringing the total land dedicated to wheat production to 1,980 ha, or 19.83 square km.

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[29] Varro, M.T. On Farming (Rerum Rusticarum). Trans. Lloyd Storr-Best. London: G. Bell and Sons, Ltd., 1912, Book I, Chapter XLIV, p. 92.

[30] Reference France Simetrica.

[31] USDA Agricultural Research Service, Nutrient Data Laboratory. USDA National Nutrient Database for Standard Reference. Release 17, 2004. "Wheat, hard white". NDB No: 20074. Available from: http://www.nal.usda.gov/fnic/foodcomp.

[32] Spurr, M.S. Arable Cultivation in Roman Italy, c.200 B.C. - c. A.D. 100. Journal of Roman Sturdies Monographs No. 3. London: Society for the Promotion of Roman Studies, 1986, p. 138-139.

Colosseum Project Walkthrough *continued...*

Table 25. Land requirement for wheat production

Caloric content	
kcal / 100 g edible portion [4]	342.00
kcal / kg edible portion	3,420.00
Sowing of wheat	
Peck / iugerum [5]	5.00
Litres / iugerum	36.48
Litres / ha	144.74
Yield 10:1 (volume grain: volume seed sown) (litres / hectare) [6]	1,447.42
Density of wheat (kg / cu. m)	800.00
Density of wheat (kg / litre)	0.80
Mass of wheat (kg) / hectare	1,157.94
Caloric content (kcal) per ha	3,960,142.86
Number of labour days per iugerum [7]	14.50
Number of labour days per ha	57.54
Caloric equivalent of labour days / ha (kcal)	173,503.82
Size of holding, iugera [3a]	200.00
Size of holding, hectares	50.40
Labour days per holding	2,900.00
Labourers per holding	9.67
Caloric requirements for workers during off-days, per ha	32,735.04
Loss due to rot and spoilage (%) [3b]	30.00
30% loss in caloric terms	1,188,042.86
Seed for harvest in following year (%)	10.00
10% harvest in caloric terms	396,014.29
Surplus caloric content per ha	2,169,846.86
Total human energy requirement	10,756,659,472.84
Annual human energy requirement	2,151,331,894.57
Hectares to fulfill annual energy requirement	991.47
Hectares required under fallow	991.47
Total ha to fulfill annual energy requirement	1,982.93
Total sq. km to fulfill annual human energy requirement	**19.83**

In total, 35.32 and 19.83 square kilometres of land under alfalfa and wheat production, respectively, would have been required in order feed the human and oxen working on the construction of the Colosseum.