

Early Imperial Roman army campaigning: observations on marching metrics, energy expenditure and the building of marching camps.

Steve Kaye, May 2017.

The observations in this essay are mainly based on the calculations derived from a spreadsheet – Roman_campaigning.xlsx available at www.bandaarcgeophysics.co.uk/arch_intro.html - and contains information about the operation of the spreadsheet.

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Note: the time format used is the International Standard ISO 8601 24 hour system, HH:MM:SS, e.g. '10:13:00' is 10 hours, 13 minutes and 0 seconds. In many instances in the text the use of seconds might seem overly precise but their use removes ambiguity, e.g. 10:13 alone could mean 10 hours and 13 minutes or 10 minutes and 13 seconds. The clock does run beyond midnight, e.g. 24:13:00 is 13 minutes past midnight. Distinguishing between a point in time and a period of time is dependent on context or preceding words, e.g. the words 'at' and 'by' typically precedes a point in time, while 'in' typically precedes a period of time. Unfortunately, there is no international standard to clearly distinguish the two.

Introduction

Early Imperial Roman armies, approximately 1st Century BC to 2nd AD, were impressive machines, powered by men, mules and horses, that traversed long distances, daily built fortified enclosures for night-time protection, and in this manner conquered much of the known western world.

This essay is intended to be read in conjunction with a spreadsheet – Roman_campaigning.xlsx (available at www.bandaarcgeophysics.co.uk/arch_intro.html) - that attempts to explain how the movement and fortification of Roman armies aided that conquest; how the men, mules and horses daily performed feats of marching and camp building that helped enable the conquest of peoples across the Mediterranean world and beyond. To that end, modern military and medical research figures relating to march velocities, rates of excavation and building, and the resulting energy expenditure and water requirements, have been sourced and factored into the spreadsheet.

The general aim of this work is to determine what Roman soldiers could reasonably be expected to have achieved in marching and building defences when the limits of modern examinations are allowed to govern the outcomes. It is not an examination of extraordinary feats, although they can be modelled in the spreadsheet.

There are a large number of parameters and metrics that govern the marching and building of defences, far too many to be described in detail, and certainly too many to discuss all of their permutations. Consequently this document will concentrate on a brief, general description of the spreadsheet, some observations arising and, in the appendices, the listing and description of the user inputs and calculated outputs.

General description of the spreadsheet

The spreadsheet caters for Roman armies ranging in size from one century (80 men) to eight legions (40,960 men). Variable velocity rates of march can be set for either on- or off-road marching using single or multi-column configurations. Times to complete the march, the energy and water consumption, and distances covered are calculated. The defensive ditch of the marching camp is V-shaped (triangular) with the option to include an ankle-breaker. The detritus from the ditch is assumed to infill a turf-constructed rampart of trapezoidal shape and, if selected, tituli. As for marching, times to complete, energy expended, etc. are calculated. As the defence construction proceeds, a match is made with extant camps in Britain allowing the examination of extant camps in terms of the size of army that could build, reasonably occupy and defend them. The user-defined variables give considerable control over many aspects of Roman army marching and camp building.

The spreadsheet contains the following worksheets:

1. 'User inputs and camp building' - the main sheet for user inputs and reported calculations (Appendices 1, 2 and 3);
2. 'March time, distance and energy' – calculations of march times, distance and energy expended (Appendix 4);
3. 'Rampart building' – calculations for the time to build the rampart;
4. 'Extant UK camps' – known marching camps in Britain used to cross-match with the calculated camps;
5. 'Pandolf 1977 calcs' – base calculations of energy expenditure for marching soldiers;

6. 'Example soldier day' – a simple description, together with timings and energy expenditure, of a typical Roman soldier's day.

From an initial selection of army size and march rate the user can alter a further 70 plus variables throughout the various worksheets (Appendix 1). For example, these range from the number of ranks and files of the marching army, the body weight of the soldier, to whether or not the latrines are dug inside the marching camp. It should be noted that the cells in the spreadsheet are not locked/protected, and that only the variables in the green coloured cells should be altered.

Approximately 70 individual parameters are reported to the user (Appendix 2) such as the lengths of the pack-mule train, the time to finish the march for the last soldier arriving at the camp, and the angle of the inward inclined sides of the rampart.

These user inputs and individual parameters are fed into the various worksheets to enable the calculation of march times, energy expenditure, the time taken to build the defences and a host of other outputs.

A brief description of the worksheet 'User inputs and camp building'

The overall strategy for the worksheet is to define a marching and camping Roman army, utilising most of the requisite parameters, many of which have been derived from modern examinations. For example, the number of soldiers arriving in the new camp per unit time is defined by the user, as is the number of diggers and rampart builders. Each digger has a length, width and depth of ditch to excavate, and the sum of the lengths for each digger determines the overall length of the ditch. This value is used to find a match between the calculated camps and extant camps in Britain. The matching extant camps aspect ratio, the ratio of side lengths, is assigned to the calculated camps. This action, therefore, applies the known evidence of Roman practice, for those particular camp sizes, to the calculations based on parameter choices and modern examinations, e.g. the rates for digging and rampart building are mostly derived from early 20th Century British Army manuals.

The worksheet allows a user to specify nearly all of the known structures and designated areas within a camp, for example, the intervallum width, the number and widths of roads and whether tituli are built. In this manner users can build a detailed virtual camp, possibly modelling an extant camp, view the results and then decide what would have been possible for the soldiers to construct.

Knowing the construction and features within allows the calculation of various outputs that give an indication of the size of armies that built the extant camps. An example is the calculated output in column AD, the orientation and number of accumulating contubernium areas which is the area mentioned by Pseudo-Hyginus, the supposed author of *De Munitionibus Castrorum* (English translation in Gilliver, 1993, appendix 1), as being required for each 8-soldier unit and their tent etc. The user can expand the width and length of the Pseudo-Hyginus area. The number of contubernium areas per user-specified army is derived and these units are fitted into the then available strigified area (the area within the camp which is available for occupation by men and beasts, i.e. it excludes the intervallum, roads and any additional area specified by the user). Column AD remains red until the strigified area is sufficiently large to accommodate the contubernium areas required by the army.

Another measure of the required strigified area for the army in question is in column AE, the percentage of the required army area that fits into the cumulative strigified area. This also remains red while the total area required, for all individual soldiers, mules, carts, latrines and horses, is greater than the available strigified area. Typically column AE remains red for a little while longer than column AD because only whole contubernium areas can be fitted into the strigified area in AD – a function of the box-packing algorithm.

Another indicator of army size for the calculated camps is column AG, total soldier density per strigified hectare, which is similar to the commonly discussed archaeological term ‘density of soldiers per hectare’ (densities of 480, 690 and 1186 soldiers per hectare are shown in columns AM, AN, AO). The difference between the two terms is that column AG relates to the strigified area while the common term is nearly always a measure of density within the rampart or ditch. The strigified area is preferred in this work because it gives measures of soldiers etc., and the individual areas they might occupy that can be modelled according to variations in intervallum and road widths. Indeed, these variations can be set to 0 m resulting in direct correspondence with the common archaeological term. Conditional formatting is also applied to column AG such that densities roughly greater than 1186 are red.

In combination the red conditional formatting of columns AE, AD and AG indicate those camp sizes that could not hold the user-defined army (Fig. 1). There are other indicators of inappropriate camps for the army, for example, the number of soldiers required to defend the rampart (column AF) and the distance between the sharpened stakes used as a palisade (column AC).; in both cases the column will turn red once logical limits are approached.

The large number of parameters and calculations in this worksheet create a vast number of permutations, far too many to consider describing. However, the spreadsheet is relatively easy to use and has many comments to aid the user.

Other worksheets are briefly described in appendices 4, Sheet 'March time, distance and energy' and 5, Other ancillary worksheets.

Distance between sharpened stakes, centre-to-centre, as palisade. (m)	Orientation and number of accumulating contubernium areas. Army needs 60 areas. READ COMMENT	% of 'required army area' that fits into cumul. strigified area (ha)	% Total soldiers (480) to defend rampart and gates	Total soldier (480) density per strigified hectare	Equivalent Extant Camps - equivalence to calculated camp and by camp perimeter distance
0.03	Square, -1	-0.23%	26.67%	-436364	Bean Burn 2
0.05	Min vs Max, -1	1.74%	30.00%	56471	Sunny Rigg 3
0.07	Max vs Max, 1	5.18%	33.33%	18972	Grindon School
0.08	Min vs Max, 3	10.09%	36.67%	9736	Coesike West 2
0.10	Max vs Max, 7	16.48%	40.00%	5963	Grindon Hill
0.12	Square, 14	24.41%	43.33%	4026	Limestone Corner
0.13	Square, 17	33.68%	46.67%	2918	Bean Burn 1
0.15	Max vs Max, 25	43.21%	50.00%	2274	Shurnock
0.17	Square, 35	56.43%	53.33%	1741	Easter Powside
0.18	Square, 44	70.53%	56.67%	1393	Walwick Fell
0.20	Square, 54	84.84%	60.00%	1158	Lugton
0.22	Square, 63	100.07%	63.33%	982	Knockcross
0.23	Max vs Max, 84	120.39%	66.67%	816	Asthall
0.25	Max vs Max, 97	140.38%	70.00%	700	Loomer Road
0.27	Min vs Max, 112	161.43%	73.33%	609	Troutbeck 3
0.28	Max vs Max, 127	184.04%	76.67%	534	Middlewich
0.30	Max vs Max, 135	189.88%	80.00%	518	Haltwhistle Burn 1
0.32	Max vs Max, 155	224.72%	83.33%	437	Hillside
0.33	Square, 172	239.46%	86.67%	410	Water Eaton Camp 1
0.35	Max vs Max, 193	279.20%	90.00%	352	Kirkby Thore 2
0.37	Max vs Max, 236	313.33%	93.33%	314	Buckton Park
0.38	Max vs Max, 264	350.61%	96.67%	280	Dalswinton, Bankfoot 2
0.40	Min vs Max, 285	380.15%	100.00%	259	Milnquarter
0.42	Max vs Max, 323	416.15%	103.33%	236	Walton Roman Camp li
0.43	Square, 307	431.58%	106.67%	228	Burlington Camp 2
0.45	Min vs Max, 378	491.20%	110.00%	200	Swine Hill 1
0.47	Min vs Max, 402	522.36%	113.33%	188	Inveravon II
0.48	Max vs Max, 427	562.94%	116.67%	175	Gleadthorpe Plantation
0.50	Max vs Max, 449	609.80%	120.00%	161	Water Eaton Camp 2

Figure 1: an example of the conditional formatting in the worksheet 'User inputs and camp building', columns AC to AH. Red indicates a limitation in the camp size or the defence of the camp for the marching army. A band of rows without red across the first 5 columns (purple header) may indicate a suitably sized camp, in this case, equivalent to extant camps (column 6) Knockcross to Middlewich.

Observations

The following observations are not in order of importance but the reader may discern a logical progression. To aid the description of the observations a set of values, mainly based on the mean values of ditches in extant camps, has been used to create a standard configuration for the camp defences. These are: ditch 1.0 m deep, 2.5 m wide, ankle-breaker 0.3 m deep and 0.25 m wide; and the rampart, 1.1 m high, 2.0 m wide, with a fighting platform 1.2 m wide and all topped by a palisade 1 m high. The spreadsheet calculations indicate that this standard configuration could have been built by all armies irrespective of size, but dependent on march rate, surface and column disposition, by assigning four diggers and four rampart-builders from each contubernium arriving at the campsite, and have completed these defences within approximately 2:42:00 between c.18:20:00 and c.18:45:00.

The mean for ditch depths of 106 extant camps is approximately one metre (1.03 m, 0.44 m SD) (Fig. 2). The spreadsheet points to a number of observations that may explain this. For one legion marching in single-column, on-road, then a ditch 2.5 m wide and 1 m deep, with an ankle-breaker 0.3 m deep and 0.25 m wide, will be completed in 2:42:05 by four diggers and four rampart-builders from each contubernium – this is the standard configuration described above. Increase the ditch depth to 1.5 m and the time taken extends to 3:52:26. Ignoring small variations due to size, all armies will have completed a 1 m deep ditch by c.18:32:00; a 1.5 m ditch by c.19:42:00. There a number of points arising from these figures. To begin with, c.2:42:00 to dig a 1 m ditch (and build the rampart – see equality observations below) might have seemed appropriate and not overly onerous to the soldiers, especially as the digging could have been shared between all the defence-building crew (modelled in the spreadsheet). The same acquiescence might have been missing for the 1.5 m deep ditch, as a finishing time of c.19:42:00 lessens significantly the time given to the evening meal and care and maintenance of kit and body. In other words, producing a 1.5 m ditch might have had a detrimental effect on morale, and the health and vigour of the soldiers, unless mitigating steps were taken. One such might have been to have the 1.5 m ditch section dug by the first half of an arriving army and the remainder completed by the second half; clearly, this option would only be available to large armies (greater than approx. 5 cohorts, 2400 soldiers). It is noteworthy that only 11 of the 106 ditches in Fig. 2 are deeper than 1.5 m, the deepest being Ward Law (area 3.8 h) at 2.4 m and width 4.5 m, which would have taken 9:14:56 to complete at c.25:19:00, i.e. after midnight. It seems reasonable to suggest that these greater depths were excavated on at least a second day unless there was an overriding need for enhanced defences, and even then, continuing to build in darkness was probably not an option. As an aside, marching camps were re-occupied and ditches sometimes re-cut and/or deepened, but even so, the mean depth is only 1 m with 34.1% extended upto 1.4 m, ergo cutting deep ditches was not an imperative for the Roman army. A likely reason was that the overall width and height of the defences above ground level was more important, and that height could be most efficiently supplied by a palisade (see observation below, ‘A high palisade on top of the rampart was essential for an effective defence system’). Note: the 106 camps may not include any re-cut and/or deepened ditches; furthermore, the depths and widths have been gathered over many decades when standards of measurement and reporting have improved; plus, the population is skewed towards the larger, more impressive, camps.

The mean for ditch widths of the 106 extant camps (Fig. 2) is 2.5 m, 1.04 m SD. Increasing the width of a ditch costs less in effort and time than increasing the depth. In the standard configuration the width is set to 2.5 m and completed by c.18:32:00. Increase the width by 0.5 m and the time taken increases to 3:02:20 with completion at c.18:45:00. As already described in the paragraph above, solely increasing the ditch depth by 0.5 m extends the completion time to 3:52:26, with a finish at c.19:42:00. Of course, this time difference between the two of approximately an hour is in

part due to the simple effect of digging nearer to ground-level, but is also due to being able to have two soldiers dig side-by-side at shallower, wider levels before being restricted to one digger at deeper levels (this is modelled in the spreadsheet). This depth-dependent limitation on digging efficiency is probably also why the ankle-breaker was dug; namely, a continuation of the triangular ditch to greater depths is costly in time and resources (energy, food, water), but digging a narrow extending slot below the triangle (or V-shape as often described) is relatively efficient, and as a trap for fallen attackers is probably more effective than the triangle shape alone. As will be discussed, the ankle-breaker is also a simple, efficient method to increase the effectiveness of the rampart and palisade.

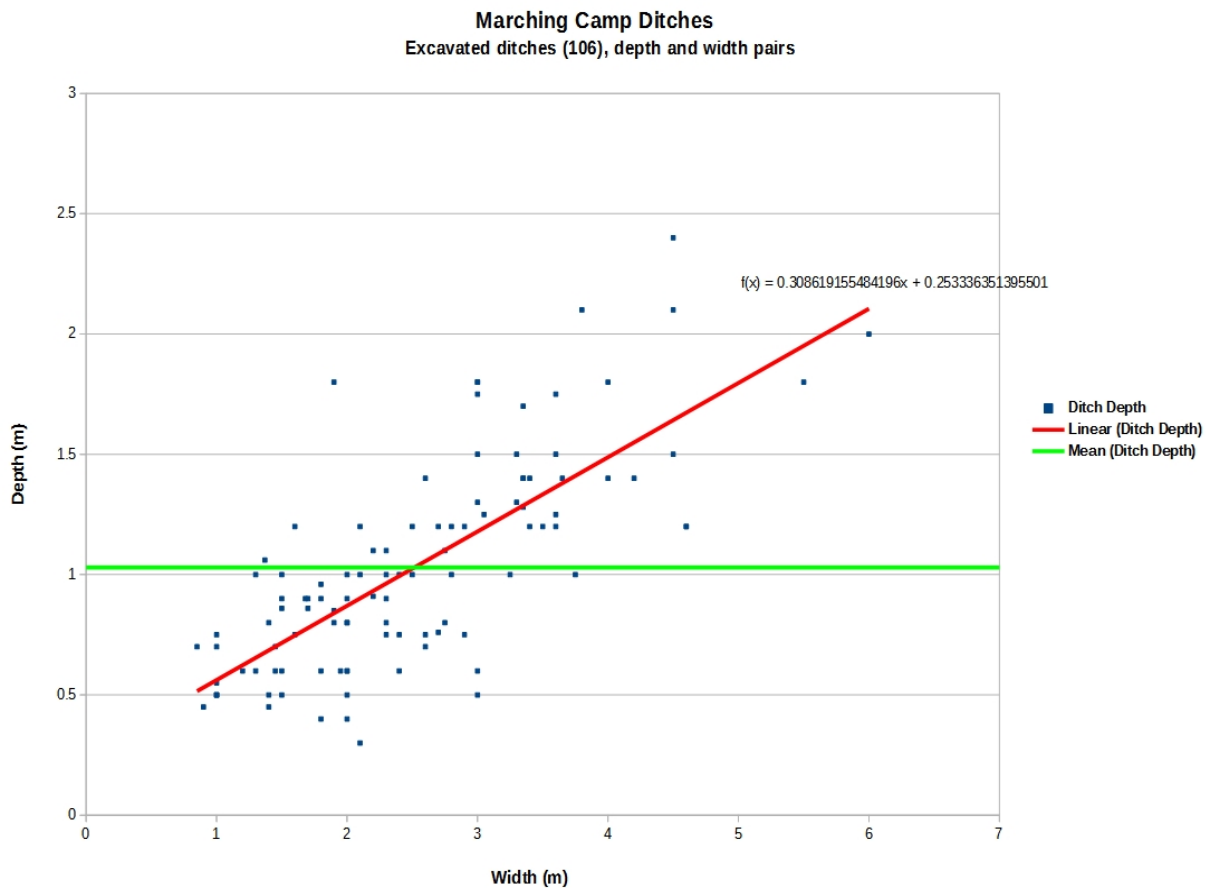


Figure 2: Excavated ditch widths and depths of 106 extant marching camps. The green line is the average depth at 1.03 m and 0.44 m SD. The average width is 2.50 m and 1.04 m SD. The red line is a trendline with $f(x)$ embedded in the graph. The areas of the camps range from Easter Powside at 0.4 h, to Lunan Head at 86 h. The deepest and widest data were selected from any reported range for a camp. Data sourced from Historic Environment Scotland (www.canmore.org.uk), National Monuments Record of Wales (www.coflein.gov.uk), Historic England (www.historicengland.org.uk) and a selection of European camps from Gilliver, 1993.

The size of the ditch does not scale with the areal size of 106 extant camps (Fig. 3). Put another way, large camps do not necessarily have large ditches and there is little correlation between area size and the size of the ditches; some small camps have large ditches and vice versa. The primary cause for this observation is the time it took to dig the ditch, itself a direct result of the effort required, i.e. a contubernium team assigned to build a section took the same amount of time

irrespective of the army size, and the amount of available time when campaigning was constrained by such factors as march distance and the time required to prepare, cook and eat the evening meal. As far as the existing excavation data allow, this observation suggests that campaigning Roman commanders thought a depth of c.1 m and width c.2.5 m was sufficient – but on its own incapable of halting leaping warriors – when combined with a palisade height of c.2 m above ground level. If correct, therefore, other reasons for the overly-large ditches must apply: for example, a shortened march distance between camps with sufficient water and a need to occupy the soldiers; an expectation of imminent attack; as a punishment detail; for repeated training sessions; or the re-occupation of camps when some ditches were re-cut. However, and not intending to lessen the forgoing reasons, a camp occupied for more than one night is full of soldiers who need employing – further improving the defences would be good for discipline, morale, strength of soldiers and defence.

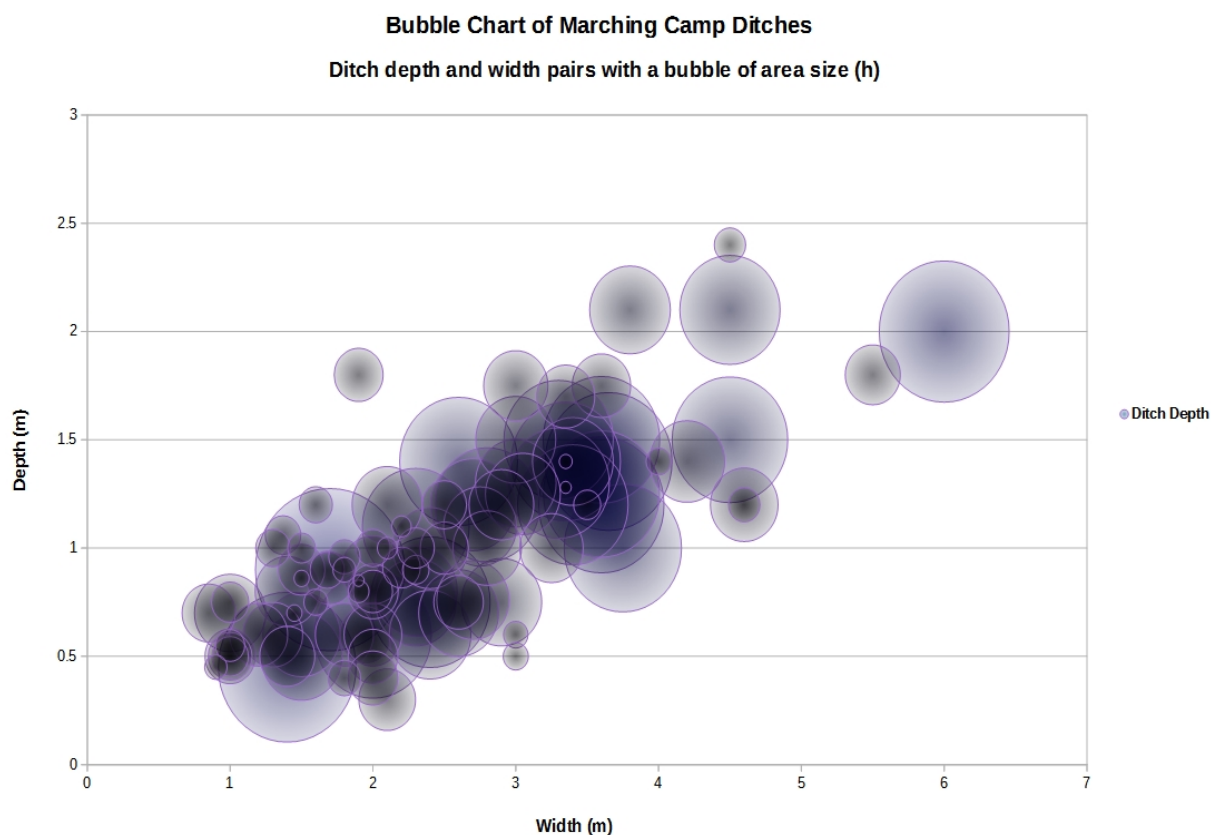


Figure 3: Bubble chart of camp area and excavated ditch widths and depths of 106 extant marching camps. The bubble size relates to the area of a camp in hectares. Otherwise the data is as Figure 2. Data sourced from Historic Environment Scotland (www.canmore.org.uk), National Monuments Record of Wales (www.coflein.gov.uk), Historic England (www.historicengland.org.uk) and a selection of European camps from Gilliver, 1993.

For armies greater than five centuries, a commonly sized one metre deep ditch and rampart defensive system took the same amount of time to build. This is partly a reiteration of an earlier observation which merits further comment. Of course, the correspondence in time to complete was simply a result of enough men completing their own sections in the same time, i.e. a contubernium of men in a small army completed their section in the same time as a contubernium in a large army,

but there are more of them in the latter, hence, a longer defensive structure finished in the same time. The size restriction arises because armies of one cohort or less do not have enough men – soldiers and slaves – to complete the standard defensive system without producing a very small camp. For example, five centuries of soldiers (400 men), and assigning all soldiers to build the defences as they arrive at the camp-site, results in an unfeasible density of 1417 men per strigified hectare, only c.70% of the area required by the army would fit into that area and only 32 of the required 50 contubernium areas would fit (Fig. 4). Furthermore, the force is insufficient to defend the rampart by nearly 50% if the defended space per soldier is 1 m, and only just sufficient, but with no reserve, if the space is increased to 1.5 m. To overcome these limitations, armies of five centuries or smaller had a number of options: decrease the sizes within the defensive structure, e.g. dig a 0.5 m deep ditch; increase the number of slaves from, the generally assumed, 2 per contubernium and have them assist in defence building; shrink road widths to, say, 4 m, enough for a cart; limit the intervallum width to a slim border around the strigified area; have the defence building crews dig two 1.524 m sections, one after another, but this option requires smaller defence parameters to avoid a very lengthy build-time, e.g. 0.5 m deep and 1.5 m wide ditch and commensurate changes in the rampart. However, these small armies probably did not individually campaign, being too small to defend themselves against most enemy forces. Furthermore, the majority of the extant small camps in Britain are situated close to the Hadrianic and Antonine walls or forts, and are usually described as construction or labour camps, which probably meant that the usual limitations, due to available time and men, did not apply.

Distance between sharpened stakes, centre-to-centre, as	Orientation and number of accumulating contubernium areas. Army needs 50 areas. READ COMMENT	% of 'required army area' that fits into cumul. strigified area (ha)	% Total soldiers (400) to defend rampart and gates	Total soldier (400) density per strigified hectare	Equivalent Extant Camps - equivalence to calculated camp and by camp perimeter length
0.01	Min vs Max, 9	2.39%	75.05%	41121	Bean Burn 2
0.02	Square, 3	-0.07%	78.10%	-1393348	Sunny Rigg 3
0.03	Square, 2	-2.07%	81.14%	-47374	Sunny Rigg 3
0.04	Min vs Max, 1	-3.62%	84.19%	-27134	Sunny Rigg 3
0.05	Min vs Max, -1	-4.71%	87.24%	-20853	Grindon School
0.06	Square, -3	-5.35%	90.29%	-18379	Coesike West 2
0.07	Square, -4	-5.53%	93.34%	-17787	Coesike West 2
0.08	Min vs Max, -4	-5.25%	96.38%	-18731	Grindon Hill
0.09	Square, -5	-4.51%	99.43%	-21783	Grindon Hill
0.10	Square, -5	-3.10%	102.48%	-31734	Limestone Corner
0.11	Min vs Max, -5	-1.44%	105.53%	-68415	Limestone Corner
0.12	Max vs Max, -3	0.68%	108.58%	144462	Limestone Corner
0.13	Square, -3	2.99%	111.62%	32826	Bean Burn 1
0.14	Min vs Max, -1	6.01%	114.67%	16348	Swine Hill 2
0.15	Max vs Max, -2	9.42%	117.72%	10438	Shurnock
0.16	Max vs Max, 1	11.37%	120.77%	8644	Sunny Rigg 1
0.17	Square, 1	18.41%	123.82%	5338	Nowtler Hill 1
0.18	Min vs Max, 6	22.97%	126.86%	4279	Carronbridge
0.19	Min vs Max, 5	27.95%	129.91%	3516	Walwick Fell
0.20	Min vs Max, 11	34.08%	132.96%	2884	Sunny Rigg 2
0.21	Max vs Max, 17	40.11%	136.01%	2450	Lugton
0.22	Min vs Max, 11	38.32%	139.06%	2565	Gallaberry
0.23	Max vs Max, 23	52.91%	142.10%	1857	Farnley 1
0.24	Square, 28	61.26%	145.15%	1604	Pantglas
0.25	Min vs Max, 32	69.33%	148.20%	1417	Haltwhistle Burn 2

Figure 4: Spreadsheet results for five centuries (400 men) building the standard defences. The red coloured cells show that the available soldiers are too few to build a camp large enough to house them. See text above for discussion. Note that the negative numbers, the consequence of trying to fit too large an army into too small a space, have not been suppressed in the spreadsheet because to do so considerably increased the computation time – such rows are to be ignored.

There may have been an equality of diggers and rampart erectors taken from the contuberniums assigned to defence-building. Furthermore, equality between the depth of the ditch and height of the turf and soil rampart, coupled with an equality of diggers and rampart erectors, results in the ditch and rampart being completed in approximately the same time. This is generally true for the modelled triangular ditch with ankle-breaker and a trapezoid shaped rampart composed of inclined walls two turves thick, front and back, the interior of which is infilled with the ditch detritus, and with a fighting platform two turves thick. Typically there is a small excess of ditch detritus that could have been used to raise the rampart or form steps, etc. These equalities would have considerably simplified the process of defence building. However, there are other rampart configurations that could have been chosen.

As a general rule, there is a greater time-cost to using earth infill in ramparts compared to filling the same volume with turves. For example, a 1.1 m high rampart with walls one turf thick, front and back, would take over two hours longer to build with a likely finish after sunset, and require an additional 2.3 m³ of earth infill per 1.524 m length section than one of the same dimensions but with two turves thick, front and back. This is due to the need to dig, carry, infill and tamp down the additional earth infill. Continuing with the example, a rampart 400 m long would require 603.67 m³ and 965.88 tonnes (density 1.65 tonnes/m³) of additional earth. Furthermore, this additional infill would have to be sourced from somewhere other than the ditch if the mean depth is accepted at 1 m. Double-thickness walls would also be more stable and robust. In consequence, **the calculations strongly suggest that the Romans would have used double-thickness turf walls.** The calculations in the spreadsheet assume that the turves were cut prior to the digging of the ditch from the area occupied by the defence complex and additional area as required in front of the ditch; this would have given the Romans sound footing within the rampart but made the approach to the defences slippery. The spreadsheet models all team members cutting turves and placing them in the intervallum ready for construction, i.e. turf cutting is the first, joint action of the whole team.

A high palisade on top of the rampart was essential for an effective defence system. As previously discussed, the spreadsheet suggests the Romans used an equality in depth of ditch and rampart height. To recap, a ditch 1 m deep, 2.5 m wide might be equalled by a rampart 1.1 m high, 2 m wide and with a 1.2 m wide fighting platform, all being completed within a few seconds of each other if there is also an equality of diggers and rampart builders. A system simple to implement and manage, and probably resulted in reliably reproducible results in most circumstances. Micro-management of soldiers would be low, and significant adjustments to sizes etc. not required; the senior officer would only have to state the depth of the ditch he required for everyone involved to know the overall dimensions of the defences (barring the lengths of sides). However, there is a problem in that a 2.5 m wide ditch and 1.1 m high rampart could easily be leapt by a charging warrior, which would result in either the warrior landing within the camp or colliding with and knocking off a legionary standing on the rampart. The warrior might die as a result of the collision, but the rampart could now be leapt by other warriors without opposition. In one rapid move the defences are rendered pointless. (Note: the average long jump distance for 16 year old boys is c.5 m., the best will jump over 6.5 m.) The simplest remedy, modelled in the spreadsheet, is to place a palisade atop the rampart made from sharpened stakes (sometimes called pila muralia) that soldiers either carried or fashioned at the new camp. Extant versions are 1.25 to 2.0 m long, waisted in the middle and tapering to sharpened points at either end. These could be thrust into the top of the front wall of the rampart, possibly to a depth of 1 m, which would anchor and support the turves, and also form a solid, protective barrier to missiles, slashing swords, poking spears and leaping warriors. The shield-equipped Roman legionary, standing directly behind the palisade, would form the mobile, active element of the defensive system; effectively, the earth, turf and palisade components were designed to protect the legionary, hence the whole camp and inhabitants. Sunk 1 m into the rampart, the palisade might have increased the height of the standard defences above ground level to 2 m

(more than the average male height), and the total height from the bottom of the 0.3 m deep ankle-breaker to 3.3 m. An attacking warrior attempting to leap a 2.5 m ditch, followed by a 2 m high defended wall, would likely fail before slithering over 3 m to the bottom of the defences. The sharpened stakes may have been used as partially buried caltrops in the front wall of the rampart, but this solution would have been less effective against missiles, could be pulled out or scaled and may not have deterred a leaping warrior, but may have been a secondary deployment option if there were sufficient stakes. Note that, unlike the form of extant ditches, the archaeological record for ramparts is poor and, of course, any recorded heights are those that remain after c. 2000 years of erosion and slumping, hence, this study and others cannot make sensible use of these height data.

The area assigned to each contubernium defined by Pseudo-Hyginus is probably too small at 31.54 m² (8.88 x 3.552 m or 12 x 30 Roman pedes). The Pseudo-Hyginus area value is sometimes used in attempts to match historical, campaigning Roman armies to extant marching camps. These attempts usually use the whole area within the ramparts while this study uses the strigified area, i.e. the area within the ditch minus areas for the rampart, intervallum, roads and any user-specified additional area. Combining the Pseudo-Hyginus contubernium area with the standard defensive structure causes the first suitable spreadsheet value of the ‘required army area that fits into the available strigified area’ (column AE, => 100%) to match the ‘soldier density per strigified hectare’ (column AG) at c.1500 for all army sizes. Note that the camp has 10 m wide roads and intervallum and that, in addition to the contubernium area calculations, there are also values for mules, horses, carts, latrines and any user-defined area. This is a very high density of men, concomitant beasts and carts, a density very unlikely to have been practised, and suggests that Pseudo-Hyginus’ contubernium area is too small. However, increasing the dimensions of the Pseudo-Hyginus area by 1 m results in a density of c.980 men per strigified hectare, a value that could be considered as more plausible.

Densities of men per hectare greater than c.1000 is unlikely to be historically valid. High densities of 1000 – 1186 men/hectare are sometimes proposed by archaeologists and historians, especially for the camps at Masada or when the density is being assessed based on the Roman actus (length, 35.5 m). However, the preceding observation paragraph suggests a more plausible limit to densities might have been c.1000, possibly c.900, because the armies defined in this study will not fit into camps that result in such densities. Unfortunately, use of the spreadsheet has failed to find a lower density limit because there are too many unconstrained variables in the archaeological and historical record, e.g. the widths of roads and the intervallum or the number of cavalry.

The larger the army the greater the number of gates required to efficiently exit the morning camp. Furthermore, the number of gates used per type may have been balanced to ensure that all column types (men, mules, etc.) exited in roughly the same time. Amongst other benefits, this would allow marching columns of men, mules and carts, of roughly similar length, to efficiently form the marching order, for example a centre of mules and carts flanked by columns of soldiers. Such balancing of columns and available gates may have been well known to the Romans. An extreme emphasises the benefits: an eight legion army exiting a camp with two gates apiece for soldiers, mule and carts could take 5:41:00. In this case the mules take over 3 hours to exit but increase the number of gates to eight (some camps have 10 or more gates), assign four to the mules, and the total exit time decreases to just over 4 hours. Of course, there is an assumption that different types were assigned their own gates, which may be correct given that beasts quickly make ground difficult for men to traverse, especially in wet weather, but for large camps this would have involved some form of traffic-control within the camp.

Roman armies were extremely efficient construction machines. This is not a unique observation but does bear repeating. For example, a single legion, multi-column marching off-road 16 km, could have excavated 7237 tonnes from a 1 m deep, 2.5 m wide ditch by c.18:57:00, thereby producing a camp the size of St. Leonards’s Hill, one of the largest in Britain, with sides 738 by 1000 m

enclosing 73.8 hectares. Only 72.30% of the soldiers, given a 1 m spacing, would be required to defend the ramparts and gates, but the density of men/hectare has fallen to 76, i.e. the camp could be built and defended, but the area enclosed is vastly greater than that required by 5120 soldiers. This efficiency arises because all the soldiers arrive in the camp in less than 20 minutes (velocity of march is 0.6706 m/sec and with a column of soldiers either side of a centre of mules and carts), and that time also separates the completion times of the first diggers from those that dig the equivalent of St. Leonard's Hill. This mathematical outcome, inherent in such modelling unless some fuzzy logic is introduced, over-emphasises the efficiency of the Roman army which in reality would have taken more time to build the camp. Nevertheless, some Roman commander of a single legion could have produced such a large camp in similar time, assuming a little metronomic activity by his men.

A single legion could march 29 km on-road, in a single-column, at a velocity of 1.2741 m/sec, and complete the standard defences, sufficient for the whole army, by c.18:25:00 and with only c.1700 soldiers having arrived in the camp. In contrast, marching in a single column off-road at a velocity of 0.6706 m/sec, would have the last soldier arrive at 22:26:00 and the defences completed by 25:05:00, i.e. the next day. Clearly then Roman armies did not march 29 km off-road in single column, but the **same army marching in multiple columns off-road could cover 16 km and complete the defences by c.18:46:00.**

An eight legion army marching 16 km off-road in multiple columns at 0.6706 m/sec could have the standard defences completed by c.18:55:00.

On-road marches of 29 km, velocity 1.2471 m/sec, were possibly limited to three legions, probably two. Structuring the marching legions for typical road widths (variable, 4 to 10 m) limits the number of files per type, for example, soldier ranks might be limited to 4 abreast, mules to 2. For a full-compliment army of three legions this results in a total column length of 23.4 km and the time taken to pass a single point is 5:06:00. Crucially, the last soldier arrives at the new camp at 20:29:00, twilight for a mid-August day in Britain. Critically, the energy expenditure for soldiers not involved in the building of defences is 5694 kcal/day, while rampart builders working for c.2:57:00 expend 6467 kcal/day and require over 12 litres of water: these figures mean the soldiers are highly stressed, especially by heat, and this level of activity is unlikely to be sustainable day-after-day. In practice the time taken may have been longer, given that maintaining march discipline over such a length of time would be difficult, hence the probability that the limit for 29 km marches was actually two legions, the last soldier arriving at 18:46:00. A pragmatic solution in this scenario to armies larger than two legions may have been to shorten the march.

Off-road, single column marching was probably rarely employed except for small armies over short distances, or where the terrain channelled the force. In contrast, multi-column marching off-road creates a compact, defensible structure which reaches its destination more quickly, and uses less energy and water than a single column army. For example, two fully complimented legions marching 20 km in single column could have the last soldier arrive at the night camp at 21:35:00, the camp completed at c.20:52:00, non-builders expend 4669 kcal/day and the rampart builders may need 14 litres of water. If the army used multiple columns the last soldier arrives at 18:31:00, the completion of the camp occurs at c.20:45:00, non-builders expend only 4320 kcal/day and the rampart builders drink under 11 litres. In both single and multi-column marching off-road the high water values indicate that the rampart builders are being dangerously heat-stressed, even debilitated, by their activities, especially by the march distance. This is further support for the observation below that c.16 km marches off-road may have been close to the norm.

Under normal circumstances the camp defences were probably completed by c.18:30:00 to allow soldiers to cook, eat, wash and repair equipment and rest during the remaining daylight hours (roughly 2:30:00 during the high-Summer). If correct, this places a further limit on distances covered and the time taken to march for the first arrivals and those required to build the defences.

March distance of c.16 km for multi-column, off-road marches would seem to be a normal limit. For example, a two legion army marching such a distance would complete the standard defences by c:18:48:00. Except for minor variations, the same is true for all armies, including those of eight legions, assuming they built the same defences (barring length, of course).

For Roman armies campaigning in Britain, and most of Europe, the observations above probably would have governed the distances marched at the tens of kilometres scale. However, the need for adequate water at the campsite would dictate the march at the single kilometre scale. Placing the camp close enough to a sufficiently large supply of water was of critical importance to the Roman army. It is for this reason that a previous study (Kaye, 2013b) found that of 307 extant camps in Britain c.66% were within 100 m of a river(s) with a flow sufficient to meet the needs of the army, and c.90% within 300 m. There are, of course, other factors that govern the placement of camps (Kaye, 2013b). In summary, a Roman army might be distance-limited at the tens of kilometres scale by the need to march on- or off-road, i.e. circa 29 km or 16 km, respectively, but further limited at the kilometre scale by water needs to march, say, only 27 or 14 km, or indeed the reverse – to march a kilometre or two further.

Discipline on the march was very important to campaigning Romans. For example, assuming a great need, a full-compliment, five legion army could march on-road for 29 km with the first soldier arriving in the new camp at 15:22:00 and the last at a tenable 20:22:00, that is at dusk in the high Summer in NW Europe. In this example the number of files for the pack mules was set at 4, but if the file number is relaxed to 2, representing a loss of march discipline, then the last soldier marches for 14:29:00, expends 5947 kcal of energy and arrives at the new camp at an untenable 22:29:00. There are similar, size-scaled effects for all other marching armies.

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Appendix 1: User inputs to the spreadsheet.

The following are the 43 parameters under the control of the user in the sheet, 'User inputs and camp building'. In the sheet the cells requiring user input are coloured green (matched below). Do not alter any other cells.

All measurements or values are metric unless stated otherwise.

The calculations for early arrivals may in many columns be negative; these should be ignored as they will turn positive for later arrivals. The negative arrivals have not been programmed out because to do so resulted in a significant increase in processing time.

The March

Parameter	Options	Notes
Army size	The pre-selected sizes start at a century with 80 soldiers, and end at 8 legions with 40960.	
Select single or multi column, on- or off-road and velocity (Normal or Quick). Note multiple column is only off-road.	Single On Normal (1.2741 m/sec) Single On Quick (1.3411 m/sec) Single Off Normal (0.6706 m/sec) Single Off Quick (0.7639 m/sec) Multi Off Normal (0.6706 m/sec) Multi Off Quick (0.7639 m/sec)	The optional velocities shown are derived from Kaye, 2013c. The designations are Single or Multi columns, marching On or Off-road at a Normal or Quick velocity, e.g, Single On Quick (1.3411 m/sec)
Input distance to march in km	Only input whole km, maximum 32 km.	Single columns marching on-road can reach 29-32 km in a reasonable time. Off-road march distances are more likely to have been approx. 16 km.
Soldiers, rank space (m)	User specified.	The distance in metres for each rank, i.e. the distance between the mid-lines of soldiers following one behind the other.
Soldiers, # of files per column	User specified.	Each member of the first rank of a marching column had a line of men following. A 4 man rank had 4 files of comrades marching behind him.
Cart length (m)	User specified	The length of a cart while being drawn and in a marching column.
Cart # of files	User specified	How many carts could march side-by-side.

Pack mule # of files	User specified	How many mules could march side-by-side.
Distance between centuries (m)	User specified	The gap of open ground between marching centuries (80 men).
Distance between carts (m)	User specified	The gap of open ground between marching carts.
Distance between mules (m)	User specified	The gap of open ground between marching mules.
# carts per legion (default 128)	User specified	User specified but the suggested number is 128. This number is applied in proportion to the size of army, e.g. if the input is 128, a cohort would have 12 carts assigned.
Number of rampart stakes per soldier	User specified. 3 is a suitable number.	Sharpened, rampart stakes may have been used to build palisades or caltrops to extend the defensive qualities of a rampart. 3 is a suitable number.
Number of rest minutes per hour	User specified. 10 minutes is common for modern soldiers.	

Time

Parameter	Options	Notes
Time to prepare before digging starts (feed, drink, etc.) (HH:M:SS)	User specified	This is the time allowed soldiers coming off the march to prepare for the erection of the defences.

Digging Crew

Parameter	Options	Notes
# soldiers per contubernium (8 man team) in construction crew	User specified	The contubernium was 8 soldiers. This spreadsheet operates at the contubernium level. The number selected here determines how many men from the contubernium were in the construction crew.
# slaves per contubernium in construction crew	User specified	It is thought 2 slaves were available per contubernium but

		this number can be increased to, for example, mimic a military working party.
# diggers from each crew (each has a section of ditch and rampart, AC13)	User specified	This number must not exceed the combined number of soldiers and slaves. Warnings are given for various issues. Try to match the number of diggers with rampart builders.

Dig rate, energy and water requirements and ditch sizes

Parameter	Options	Notes
Space or section per digger (m)	User specified	<p>The section usually extends lengthwise along the ditch. Have to allow space for diggers working next to each other. Suggested minimum might be 1 metre for a section rotated 90 degrees to the ditch length. This would decrease the time to complete the whole ditch.</p> <p>British Army standard is 5 ft (1.524 m). Double this number to calculate effect of dig/rampart crew working on two sections sequentially.</p> <p>Or, a doubled number also mimics the effect of an initial crew being relieved by later arrivals. This only applies to armies with sufficient men.</p>
Rate of digging (m ³ /hr)	User specified	<p>WWII British Army rate of digging was 0.4 m³/hr on difficult earth to 0.7 m³/hr on easy ground; Royal Engineers' assessment in 1993 and 1996 was 0.3 m³/hour (0.15 m³/hr for chalk or rock). Roman soldiers were probably proficient therefore the suggested default is 0.5 m³/hr.</p>
Number of rest minutes per	User specified	More than 10 minutes would

hour for construction crew		probably be exceptional.
Ditch width (m)	User specified	
Ditch depth (m) to bottom of calculated isosceles triangle, i.e. does not include 'ankle-breaker'	User specified	Calculations for the ditch are based on an isosceles triangle. Height of triangle based on the ditch depth.
Depth of ankle-breaker (m)	User specified	Typical depths range from 0.2 to 0.4 m. May be absent.
Width of ankle-breaker slot (m)	User specified	Always found to be less than depth. 0.25 to 0.3 m is a typical measure.
Space for soldiers defending rampart (m)	User specified	The space occupied by defending soldier on rampart. Suggested minimum = 1 m (shield was circa 0.75 m chord length). 1.25 m might be a typical value (no evidence).
Width of intervallum and rampart (m)	User specified but be aware that the number input must allow for the width of the rampart, AO13.	Rampart width (which is notified) is set elsewhere (AO13), therefore, this number should exceed that.
Diggers energy expenditure (kcal/hr)	User specified	Default value is 640 kcal/hr derived from figures for farm manual labourers weighing 80 kg (the weight of an example legionary).
Rampart builders energy expenditure (kcal/hr)	User specified	Default value is 480 kcal/hr derived from figures for gardening manual labourers weighing 80 kg (the weight of an example legionary).

Rampart Building

Parameter	Options	Notes
Width (m)	User specified	Extant rampart widths range from 1.5 to 3.5 m. Width is from the front of rampart to the rear.
Height (m)	User specified	Difficulties with sufficient time and infill be found if the height much exceeds 1 m.
Width of fighting platform (m)	User specified	The platform from which a soldier patrols or defends the

		rampart. Width is from the front of rampart to the rear.
Height of palisade above rampart (pila muralia) (m). Click and select.	User specified.	Average height of sharpened stakes is 1.25-2m. They could be deployed as caltrops, c.2m high, or half buried for stability as a palisade on top of the rampart, in which case the height might be 1 m.
Select the distribution of turves in rampart (click and select)	Click and select from the following: 1) 2 turves thick front and back 2) Two turves thick front, one back 3) One turf thick front and back 4) 2 turves thick lower half-height, one thick upper half-height, front and back.	Excavation evidence shows that ramparts were built using turves but not how they were distributed. The generalised model employed in the spreadsheet is that the detritus from the ditch infilled, some times partially, a turf enclosed shell. The user selects the form of this shell.
WARNING: Cell below turns red if m3 of rampart is full of turves, i.e. no space for ditch detritus		
WARNING: Cell below turns red if insufficient ditch detritus to infill rampart. Delta volume below (m3).		

Camp road widths; use or not of tituli; some occupation sizes.

Parameter	Options	Notes
Width of Via Principalis (m)	User specified.	The width of the road also governs the size of the corresponding gate (road width plus 2 m) in the defences.
Width of Via Quintana (m)	User specified.	The width of the road also governs the size of the corresponding gate (road width plus 2 m) in the defences.
Width of Via Praetoria (m)	User specified.	The width of the road also governs the size of the corresponding gate (road width plus 2 m) in the defences.
Width of Via Sagularis (m)	User specified.	The Via Sagularis was an encircling road system inside

		the defences and had, probably, no gates.
Width of border for long side of contubernium area (m)	User specified.	This is the free space along the long side of the area assigned to each contubernium i.e. tent, fire place, mule space, kit space, etc.. The contubernium long side is set to Hyginus' 30 pedes (8.88 m).
Width of border for short side of contubernium area (m)	User specified.	This is the free space along the short side of the area assigned to each contubernium i.e. tent, fire place, mule space, kit space, etc.. The contubernium short side is set to Hyginus' 12 pedes (3.552 m).
User specified areas (m2) for additional space in strigified area.	User specified.	Input additional area (in sq. metres) for officer's space, more mule space, or quaestorium, etc. This is an absolute value and is applied to the cumulative calculations often resulting in negative values for calculated areas etc. The negative effect will diminish as larger numbers of soldiers arrive at the campsite.
Use gate tituli or not? Answer Yes or No below. Dimensions match ditch and rampart.	Choose yes or no from the dropdown.	The tituli are calculated for each gate and the length set to the gate width (road width plus 2 m). There are no gates or tituli without a corresponding road. The dimensions of the tituli match those for the ditch and rampart.

Latrines

Parameter	Options	Notes
Calculate required latrines inside the camp? - Yes or No	Click and select – yes or no	Selecting 'Yes' will cause the area required for latrine straddle-trenches to be included in the strigified area of the camp. 'No' means the latrines were external to the camp.

Appendix 2: Individual reported parameters.

The following are the 49 parameters individually reported by the sheet, 'User inputs and camp building'. They are not input by the user. In the sheet these cells are coloured light-brown.

All measurements or values are metric unless stated otherwise.

The March

Parameter	Notes
Legion's size (relative to 1 Legion)	
# soldiers	Total number of soldiers in army.
# Soldier Ranks	Number of ranks in the marching army.
Length Soldier's column (m)	Calculated from number of ranks, rank space, century space and the multiplier applied to the column(s).
# Cart	
# Cart mules	
Length cart column (m)	
# Pack mules	
# Mules total	The total number of mules in the army.
Length pack mule column (m)	
Length total baggage (m)	Total length of pack mules and carts.
Total Column Length (m)	
Total Column Length (miles)	
Time column enters camp or passes a point (decimal mins)	The total time for the whole column to march past a fixed point or enter the camp. 'Pass' is applied similarly to parameters below.
Time column enters camp or passes a point (HH:MM:SS)	As above.
Time soldiers enter camp or pass (mins)	
Time soldiers enter camp or pass (HH:MM:SS)	
Time (sec) each rank enters camp	
Time (sec) each crew to enter camp Number of soldier columns.	Crew = number of diggers and rampart builders
Number of soldier columns.	For multi-column off-road marching change number of columns in sheet 'March time, distance..' D51.

Time

Parameter	Notes
Time of 1st arrival	1st soldier to arrive in the camp. Derived from sheet 'March time, distance, energy'.
Time of last arrival	Last member of army to arrive in the camp. Derived from sheet 'March time, distance, energy'. These times are for the whole army, not just the soldiers.

Digging Crew

Parameter	Notes
# Total soldiers plus slaves digging or raising rampart.	All soldiers in the construction crew.
# soldiers per contubernium on other duties.	Number of soldiers NOT in the construction crew.
# soldiers and slaves building rampart	Number of men just building the rampart.

Dig rate, energy and water requirements and ditch sizes

Parameter	Notes
Volume of each ditch and ankle-breaker segment (m3)	
Time to cut turf above ditch and dig each section. NOTE: volume of ditch greater than 1.25 m wide is dug by 2 men, side-by-side.	The time to cut turf has been estimated because no reliable figures could be found. Turves are 444 x 296 x 148 mm in size. The estimated time/per man/per sq. metre = 120 secs to cut turves vertical borders with dolabra axe; 15 seconds to cut one turf with dolabra adze; total time to cut = 234.1344 secs. There are 7.61 turves per sq. metre.
Weight of excavated material per section (at 1.6 tonnes/m3)	1.6 tonnes/m3 is a reasonable average density for soil.
Energy expenditure for soldiers not digging or building (kcal/day)	Kcals required, and consumed, per day for a soldier marching the stated distance and performing camp duties but not involved in constructing the defences. The kcal/day figures are for an example legionary of 80kg weight, 40 kg armour, arms and all other kit. See Kaye, 2013c. Derived from sheet 'March time, distance, energy'.

Energy expend. sole diggers (kcal/day)	Kcals required, and consumed, per day, for a man who digs the ditch alone. The march is included. The reported figure probably errs on the low-side.
Energy expend. rampart builders (kcal/day)	Kcals required, and consumed, per day, per man building the rampart. The march is included. The reported figure probably errs on the low-side.
Water required for crew-members (ltr/day)	Litres of water expired, and consumed, per day, per man for all crew members assuming that the digging was shared equally between all of the construction crew.
Water required sole digger (ltr/day)	Litres of water expired, and consumed, per day, for a sole digger who works until the ditch is complete.
Total water (ltr), 24 hrs, for all men and beasts	
Length saved by curved corners plus width of roads (plus 2 metres) as gates	All computations in the spreadsheet of length, area etc. and all derivations are for a marching camp with curved (playing card shaped) corners. Curved corners require less ditch length compared to 90 degree bends by approx. 8 m per camp. Gates in the defences have a width of the associated road plus 2 metres. This value is added to 'cumulated ditch length' along with the computed width of roads. There are no gates or tituli calculated without a road requiring an exit or protection (if selected in BF13).

Rampart Building

Parameter	Notes
Length of rampart section (equals length ditch section x # diggers) (m)	The rampart section to be built is defined as the length of each dug section of the ditch, times the number of diggers. For example, of a total construction crew of 8 men, 4 are diggers each digging a length of ditch 1 m long, giving a 4 m total ditch length. The remaining crew (4) are rampart builders and they collectively work to raise 4 m of rampart and palisade.
Total height above ground level of rampart defences (m)	The height of the rampart and palisade on top.
Total vertical height from base ankle-breaker to top of rampart defences. (m)	
Total time to build rampart (includes turf production). (Hours decimal).	The total time to: remove and move turf above ditch; remove and move turf elsewhere; move

	detritus from ditch to rampart; ram the detritus infill; lay turves.
Time delta (secs) for rampart and ditch (neg = rampart takes longer). Mins below.	All construction crew members begin the task by jointly removing turf from on top of the ditch. The diggers then start their work. This time delta figure accounts for the shared work. If the ditch diggers finish before the rampart builders then the diggers help finish the rampart.
# rampart builders	Number rampart builders.
Angle of inward inclined sides. (Degrees)	A turf wall retains the material inside it and supports itself by sloping inwards as it rises, i.e. the base will be wider than the top. Experience in Britain (Devon Banks) suggests that a common slope is approx. 75 – 80 degrees. Walls approaching 90 degrees will be prone to failure depending on the height. A turf wall commonly has a batter, a concavity to the vertical face, but this is not modelled in this spreadsheet.
Delta of ditch detritus and infill volumes (neg = not enough from ditch). (m3)	If the ditch detritus is less than that required to fill the non-turf interior of the rampart then a warning is given in cell AU13. A warning is given in cell AT13 if the whole rampart is filled with turves, i.e. no space for the detritus.
Max. time when defences completed (HR:MM:SS).	Time when the whole defence circuit is completed. The rampart can only be completed once the last of the ditch detritus has been dug. Therefore the time shown here will match that for ditch digging unless the rampart takes longer to erect.

Latrines

Parameter	Notes
Weight of human dung (Mg (tonne), daily)	For all men, soldiers and slaves.
Volume of human dung (m3, daily)	
Total length of straddle-trench latrines required	Calculation based on US Army manuals (WWII era).
Total area of straddle-trench latrines required (ha)	Users can choose (AY16) whether this area is included in the calculations related to the strigified area.
Total length of tituli for all gates with widths greater than 0 m.	Roads give rise to gates which may have tituli (BF13).

Appendix 3: Calculations from inputs described in appendices 1 & 2.

In sheet 'User inputs and camp building' there are 50 columns of parameters described in row 20 from column B to AY. The numbers calculated start at row 21 and extend until all soldier ranks of the army have arrived at the camp site. The calculate area stops at row 3997 but could be extended if necessary.

The calculations for the construction of the defences is based on a contubernium crew completing their allotted tasks and then preparing their tent etc. for the night. However, a crew can be allotted a second section to build by doubling the number for 'Space or section per digger' (AC13). This might be required for small marching units, e.g. those less than 3 centuries (240 men).

If the army was sufficiently large then a contubernium crew might have been relieved by a new crew after, say, one hour, but the time to complete the defences would have remained the same. The main benefit would have been a decrease in the amount of food and water required by the men (depending on the size of the defences and the ratio of crew digging time to the time to complete the defences).

One of the main aims of the spreadsheet is to calculate what groups of soldiers could physically achieve and match this to extant marching camps, hence, there are two broad sets of calculation columns: those coloured grey from B20 and those light blue from AH20. The grey columns are for parameters derived from the user inputs and used to define the groups of soldiers and their activities. The cumulative length of the calculated camp circuit is then used to find and match to the total ditch length of extant marching camps. These camps are named, and other parameters are calculated and displayed, in the light blue headed columns.

Parameter	Notes
Time of arrival at camp site for each rank	Look-up in 'March time,distance, energy for distance and either single or multi-column marching.
Time start ditch and rampart	Governed by 'Time to prepare before digging...' (W13)
Soldiers yet to arrive	Decrements number of soldiers in army by ranks arrived.
Cumulative crews	Number of crews derived from already arrived ranks.
MOD remainder	A bit of required maths.
Cumulative # diggers	
Cumulative soldiers in ditch and rampart crew	
Ditch plus rampart crew as % of total soldiers	Cumulative %. of total soldier number.
Cumulative soldiers in camp	All soldiers, building or otherwise, in the camp.
Cumulative ditch+rampart slaves in camp	Number of slaves building defences.
Cumulative dug ditch length	
Cumulative length of camp circuit (includes	Length of camp circuit defined by the ditches

length of gates) (m)	and any gates.
Camp circuit min. side length (m)	Calculated from the minimum side length of corresponding extant camp by ratio of sides.
Camp circuit max. side length (m)	Calculated from the maximum side length of corresponding extant camp by ratio of sides.
Cumulative volume of finished ditch (m ³)	
Time when ditch completed	The time when each ditch section is completed. When the ditch is completed the diggers assist rampart crew.
Time when rampart completed	The time when each rampart section is completed. The rampart can only be completed once the last of the ditch detritus has been dug. Therefore the time shown here will match that for ditch digging unless the rampart takes longer to erect.
Cumulative total tonnage excavated	
Area within camp circuit = dug ditch + gates (ha)	The 'camp circuit' is the dug ditch with rounded corners and all gates (length of the road width + 2 m). The area is calculated the ratioing of the calculated with extant marching camps, i.e. Ratio of perimeter = Ratio of Sides. Ratio of Sides squared = Ratio of Area.
Area of intervallum and rampart (ha) (includes gates)	
Area of roads within strigified area (ha)	
Strigified area (ha) (excludes intervallum & roads)	Strigified area = area within camp circuit that is not road or intervallum, i.e. it can be used for occupation by men and beasts.
Length (m) of MIN side of strigified area, minus road widths	This is strigified area's minimum side length MINUS the width of roads. Roads not included because this value is used to calculate the number of contubernium areas that will fit into the strigified area.
Length (m) of MAX side of strigified area, minus road widths	This is strigified area's maximum side length MINUS the width of roads. Roads not included because this value is used to calculate the number of contubernium areas that will fit into the strigified area.
Ratio of 'Area within camp circuit' given to strigae (REDUNDANT)	A REDUNDANT FUNCTION. This ratio is used to calculate the corresponding extant camp's density of soldiers per hectare figure, e.g. 'Extant camps, # soldiers -density 480/ha' in column AM.

Density of cumulative soldiers per strigified hectare	The number of soldiers that have arrived divided by the then existing strigified area.
Strigified area (sq m) for each of the army's soldiers	The amount of space for each soldier in the then existing strigified area.
Distance between sharpened stakes, centre-to-centre, as palisade. (m)	This distance applies to a palisade made of sharpened staves on top of the rampart. A distance approaching and exceeding 0.3 m will cause cells to show red.
Orientation and number of contubernium areas.	This column shows the optimum way to pack the contubernium areas into the strigified area (W), e.g, Max vs Max, 966 = the orientation followed by the number of contuberniums (tents plus living space) that fit into the strigified area.
% of 'required army area' that fits into cumul. strigified area (ha)	The 'required army area' is the occupation area – tents, areas for mules, etc. - and is calculated for soldiers, slaves, horses, mules, carts, latrines and any additional area specified by the user in BE13.
% Total soldiers to defend rampart and gates	The user can select the space for each soldier on the rampart (AJ13) which is assumed to be only 1 soldier deep, but the gates are defended 4-deep (fixed). Beyond 75% the cell colour turns red suggesting a lack of reserve force to defend the rampart.
Total soldier density per strigified hectare	This value is similar to the often used 'density of men per hectare' used in extant camp examinations; except that this density relates to the strigified area (area within the camp circuit that is not the intervallum or roads). Cell colours will be red for very high densities, through yellow for densities of 1186 to 480 and then white.
Equivalent Extant Camps	The names of extant camps whose ditch length equals, or is close to, the circuit length of the calculated camp.
Extant camps ditch length	As reported by various agencies, e.g. Historic England.
Extant camp min side (m)	As reported by various agencies, e.g. Historic England.
Extant camp max side (m)	As reported by various agencies, e.g. Historic England.
Extant camps hectares	As reported by various agencies, e.g. Historic England.
Extant camps, # soldiers - density 480/ha	The number of soldiers in the camp if the density was 480/ha.

Extant camps # soldiers – density 690/ha	As above but density of 690 men per ha.
Extant camps # soldiers - density 1186/ha	As above but density of 1186 men per ha.
Extant camps # soldiers plus slaves – density 480/ha	As above but includes slaves at a density of 480 men per ha.
Extant camps # soldiers plus slaves – density 690/ha	As above but includes slaves at a density of 690 men per ha.
Extant camps # soldiers plus slaves – density 1186/ha	As above but includes slaves at a density of 1186 men per ha.

Appendix 4: Sheet 'March time, distance and energy'.

The sheet 'March time, distance and energy' calculates those parameters for differently sized Roman armies either on- or off-road and in various configurations, e.g. single column or multi-column. Times of the first and last arrivals at a new marching camp location, and energy expended during the march, are passed to the sheet 'User inputs and camp building'.

As in other sheets, only the green coloured cells are for user inputs.

There are four, purple-banded calculation sections which stretch from column D to EC. These are:

- 1) FOR ARMY UNITS MARCHING IN SINGLE COLUMN EITHER ON- OR OFF-ROAD
- 2) FOR ARMY UNITS MARCHING OFF-ROAD WITH BAGGAGE TRAIN OF MULES AND CARTS FLANKED LEFT AND RIGHT BY SOLDIERS, A RECTANGULAR FORMATION
- 3) FOR ARMY UNITS MARCHING OFF-ROAD WITH SOLDIERS IN FRONT FOLLOWED BY MULES AND CARTS (ALL CAN BE PARALLELED BY THE MULTIPLIER)
- 4) FOR ARMIES MARCHING OFF-ROAD BUT WITH UNITS SEQUENTIALLY JOINING A ROAD (ONE AFTER ANOTHER) WITH SOLDIERS IN FRONT FOLLOWED IN SERIES BY CARTS AND MULES (ALL CAN BE PARALLELED BY THE MULTIPLIER)

Only sections 1), single column marching, and 2), multi-column marching, are fed back to the main sheet 'User inputs and camp building'. The other sections, 3) and 4), are for user reference and experimentation; note that some variables are passed to these sections from 'User inputs and camp building'. The pale yellow rows at 26, 61, 98 and 139 are for armies defined in 'User inputs and camp building'. Otherwise the calculations are for one to 16 armies.

Within each section are calculation blocks for a) The length of the columns, b) Time to exit camp, c) Marching times for first and last ranks, d) Arrival times, and e) Energy expenditure for the march etc. (does not include that for building defences).

Section 2) has green, user input cells that control the number of columns for soldiers, carts and mules that march off-road. Altering these column multiplier values causes changes in the time taken to exit the over-night camp and complete the march distance. Most significantly the multiplier for the soldiers is fed back to the main sheet 'User inputs and camp building' which controls the number of soldiers arriving in unit time, e.g. a column multiplier value of 1 means the army

baggage train is flanked by two columns of soldiers, one either side, and if the number of files per column is 8 then 16 soldiers will arrive at the new camp in unit time. A value of 2 doubles the number of soldier columns to 4, i.e. 2 columns marching either side of the baggage train, and 32 soldiers will arrive in unit time. For single-column marching, section 1), the column multiplier is not applied (more strictly, it is set to 1).

Appendix 5: other ancillary sheets

The sheet 'Rampart building' primarily calculates the time to build the rampart defined in 'User inputs and camp building'.

The sheet 'Extant UK camps' is a list of known marching camps in the UK (last updated for the year 2013). It is an edited list with some known camps omitted because, for example, the length of sides is not well defined.

The sheet 'Pandolf 1977 calcs' calculates the basis for energy expenditure values for marching soldiers. There are also tables, the values of which alter according to user-specified changes, for example, the body or load weights of the marching soldier. Note that these changes will propagate through the workbook.

The sheet 'Example soldier day' contains a simple table of daily events, their timings and associated energy expenditure.

Appendix 6: Fixed parameters in the spreadsheet.

The following are parameters that are significant, fixed and usually hidden in the spreadsheet. Most can be altered if required.

Fixed Parameter	Value or State
Number soldiers in legion	5120
Number of men in contubernium	8
Size and area of contubernium space in camp	8.88 x 3.552 m, 31.54176 m ²
Area for each mule in camp	6 m ²
Area for each horse in camp	8 m ²
Area for each cart in camp	18 m ²
Normal on-road march velocity	1.2741 m/sec
Quick on-road march velocity	1.3411 m/sec
Normal off-road march velocity	0.6706 m/sec
Quick off-road march velocity	0.7639 m/sec
Water required for 1 hour of digging	1.2 ltr
Water required for 1 hour of marching	1.0 ltr
Mass of excrement/solids man per day	0.498 kg
Volume of excrement/solids man per day	0.5909 ltr
Size of turves in rampart	444 x 296 x 148 mm

Fixed Parameter	Value or State
Weight of turves in rampart	18 kg
Time to cut and move 1 m ² of turves	5.9022 minutes
Time to lay each turf	3 seconds
Volume of moved earth (ditch to rampart)	1.5 m ³ /man/hr
Spreading earth infill in 150 mm layers	1.75 m ³ /man/hr
Ramming infill in 150mm layers	1.75 m ² /man/hr