

PERFORMANCE OBSERVATIONS OF THE BEIJING AREA'S UNRESTORED GREAT WALL: 'RAMMED EARTH AND RUBBLE CORE'

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Abstract: This paper presents the author's observations of selected sections of the Great Wall around Beijing, specifically the condition of the rammed earth core and the factors which have and are affecting its present condition-longevity.

Keywords: Great Wall, unrestored Great Wall, rammed earth core, durability, Hakka Tulou, rammed earth, earth structures

1 INTRODUCTION

Over the past six months I have had the opportunity to visit and study the Beijing areas Great Wall on upward of 25 occasions. Almost exclusively these visits have taken place on unrestored sections, which of course constitutes the vast majority.

The Beijing area Great Wall incorporates Rammed Earth into a modern looking structure and, aside from the use of fired bricks, is environmentally sustainable and has proven structurally stable over a very long period.

Obviously to observe the Wall's Core, the Walls exterior needs to have failed to some extent. As the stone and brick exterior is in various stages of failure, it is possible to view the Core through various stages of exposure. Some sections however are still fully intact. These intact sections have normally succumbed to some degree of movement. In this case, the interaction between the outer shell and the Core can be observed.

The Great Wall's different components function superbly as an integrated unit. Separating them for study, even after they themselves have separated, fully or partially due to failures, is a much more difficult task than anticipated, which is a testament to the incredible engineering feat the Wall was and still is today.

However, as the Wall consists of two basic parts, the outer brick and stone, and the inner Core, each is described in turn, and then followed with observations and comments. As the title suggests, this paper discusses the performance observations of the Great Walls "Rammed Earth and Rubble Core". It is by no means a scientific or even methodical study. But simply observations of behavior and performance based upon the authors general knowledge and experience.

2 THE OUTER BRICK AND STONE SKIN

The integrity of the Walls outer skin after such a long period of exposure to the elements, especially without any maintenance is very impressive. There seems to be many reasons for its longevity, these are listed below. To begin I will briefly describe the construction materials and techniques as observed.

Fired bricks of approximately 285x145x90mm form the exterior of "most" of the studied sections and most of the great wall in the ranges North of Beijing. (Figures 3 and 4) A small portion of the studied Wall is built

entirely of stone with a Rubble Core. (Figures 1 and 2) However a unifying factor between these sections, aside from a Rammed Earth or Rubble Core, which is the use of Sticky-Rice Lime mortar. (Figures 1, 3, 4)



Figure 1



Figure 2



Figure 3



Figure 4

Depicts the liberal use of the mortar between courses of paving which form the Walls walkway. (Figure 5) There are three and sometimes four courses of paving laid over the Walls Core, forming the walkway. Under this is normally a rubble base, often itself laid in the mortar. Deeper still the Core proper consisting of more Rubble, sometimes of a different stone type and/or Rammed Earth.

The Sticky-Rice and Lime Mortar has incredible properties, not least among them it ability to repel water. Without the superior nature of this mortar, it is doubtful that much of the wall would remain today. This mortar is used throughout the entire wall from the rubble and stone foundation, (Figure 6), to the brickwork and paving.



Figure 5



Figure 6

Quarried stone blocks serve as the foundation for the entire Wall studied. Often many courses are used; perhaps where it is plentiful, where not, as few as one course is set in place, upon which the bricks are laid. The foundation stones vary in size shape and type considerably. (Figures 1, 3) The foundations themselves are undoubtedly well constructed which is clearly visible in many places where they are built straight onto bedrock. Due to the longevity of the Wall, the foundations placed on soil are undoubtedly well constructed also. Apart from a few locations where the soil has subsided but the Wall remained intact, they are not visible, and therefore not observed in this study.

There are some minor differences in the materials and construction of the Wall's exterior. These differences are presumably due to the utilisation of the vernacular materials available (such as the amount and type of suitable stone). Other factors such as the period of construction, the particular individual(s) in charge of a section and the speed of construction have presumably contributed to the observed variations.

Factors contributing to the failure of the outer skin: 1) Roofs from towers have been removed, burnt or decayed allowing water to penetrate. 2) The bricks and or pavers have disintegrated causing the walls collapse or water to enter the Core. This is sporadic and localized, presumably as a result of inferior raw materials, workmanship, or both. 3) The mortar has failed resulting in the failures stated above. 4) People have deliberately removed bricks and pavers. (During the Cultural Revolution, local villagers were actively encouraged to do so). 5) Subsidence of the soil beneath the external walls. (At least 90% of failures seem to be due to this point alone). Note: All of the ground movements discussed in this paper are assumed to be, and therefore treated as non-uniform in nature. As it is this type of movement that has caused by far the most damage to the Wall and Core. 6) Where the external wall are built with an incline of greater than approximately 5 degrees off plumb, the parapet wall have very often collapsed inwardly. This collapse allows water to enter the Core at what seems to be a very vulnerable location. 7) Isolated instances of poor quality construction-workmanship. This is mostly evident in the varying quality of the bricks and to a lesser extent the mortar.

Factors contributing to the longevity of the outer skin: 1) The Walls builders were obsessively fastidious with draining water away from the top of the wall. As a result, there is no observed evidence of any failure of the outer skin due to rainwater penetration if the paved walkway has not been removed, the roofs of towers removed, or the outer walls collapsed. 2) The squat dimensions of the Wall, the curves and bends along its length, the bracing effect of the Core and the fact that the majority of the walls are not freestanding all greatly contribute to its stability. 3) The Beijing area has a very dry winter with most rainfall falling during the summer. The Wall can therefore readily evaporate most rainfall. 4) Except in very few locations where the mortar quality is poor, the Sticky-Rice Lime Mortar is seemingly impervious to water, therefore very resistant to the freeze thaw cycle. 5) For many centuries, the mortar has effectively resisted the growth of vegetation and root invasion within the joints. 6) Despite being strong, the mortar is still flexible enough to bend with a moving wall thus avoiding some structural damage. 7) War, vandalism, and seismic damage are largely absent. 8) Wear and tear seems very minimal. 9) The Wall is almost entirely built on ridgelines, normally rocky in nature, therefore ground or running water have not moistened the Wall or the ground on which it is built. 10) The rocky ridges provide excellent foundations. Where the Wall is built onto rock, the outer walls have not parted from the Core. 11) The fired bricks are never in contact with the natural ground. Therefore, they are unlikely to wick water and sustain damaged by evaporating salts or freeze thaw. 12) Well-prepared foundation. 13) The Rammed Earth and Rubble Core seemingly adheres to the outer brick walls with considerable force, presumably through keying and suction, whereby assisting in preserving the structural integrity. (The parapet walls will often fall away due to gravity) (Figure 11) Therefore, despite some seemingly impossible angles of outward lean, (almost exclusively due to ground subsidence) the walls are very reluctant to separate and collapse. It is observed that the outer wall is far more likely to separate from the Core by slipping away, than collapsing outwardly. Presumably, a great force, up to the entire weight of the outer wall, is exerted if there is a slipping action, resulting in this being a more common failure.

3 THE RAMMED EARTH AND RUBBLE CORE

Some of the Great Wall's Rammed Earth and Rubble Core is now exposed. Clearly, it was not the intention of the Walls' builders that the Core be exposed. Therefore, insight might be gained into the inherent qualities and/or weaknesses of Rammed Earth by observing the weathering characteristics and failures of a Rammed Earth and rubble Wall not designed to stand on its own, or stand exposed. Unfortunately, the length of time

these sections have sat exposed is unknown to the author. It would clearly be very helpful if this could be established.

The Core sections visited in this studies area possess stability inducing dimensions. (Approximate width to height ratio of between 1/1 and 1/3). Therefore, the width to height is considerably greater than a typical Rammed Earth Wall. The inherent stability gained from such a squat wall is significant and obvious. There seems no doubting that a considerable portion of the Core's robustness and the Wall's longevity can be contributed to this fact alone.

As stated above, it is observed that almost without exception, Walls collapsing, either slipping or falling away, is due to ground settlement. As stated above, these collapses almost always occur a location where the ridge is at its steepest and where the Wall is built onto earth. Therefore it is in these locations where the greatest amount of Core is visible. (Figure 7, 8, 12) Unlike the generous average Core dimensions, the areas of exposed Core are often more narrow than the average as the Wall itself is often more narrow at these locations. The exposed sides have sometimes been torn away during the outer walls collapse or subsequently subsided themselves. Despite this, no complete collapse in the study area was observed although some modern preventive repairs have been carried out in places.

The Core, as stated, is constructed of Rammed Earth and Rubble, with the emphasis on constructed. Whilst the Rubble component varies wildly, every inch of the observed Core is constructed in a very deliberate and skilled way. It is often obvious why the builders have used Rubble as opposed to Rammed Earth in many sections. At the top of a rocky ridge, earth is in short supply. However, in a few locations, (Figure 7) rubble abruptly stops and Rammed Earth begins. No immediate logic for this is apparent, perhaps further investigation will reveal the answer.

Where the Rubble is a robust and angular rock, it appears to have also been encased in the same soil as used in the Rammed section, and likewise rammed into place. (Figure 8) No visible difference in strength between these Rubble or Rammed sections is evident. However, some difference in weathering and erosion is evident with the Rubble sections performing better. (Figures 7, 8)



Figure 7



Figure 8

It appears that no rock has been rejected as Rubble. Slate, shale, whatever is available within a reasonable distance of construction site was utilised. However, the construction techniques were carefully adapted to suit the available Rubble fill. Although, where building across the above mentioned steep ridges with an earth foundation, great care seems to have been taken to construct a Core of considerable tensile strength even if this necessitated carrying in the appropriate material.

Where the Wall is built directly onto bedrock, and particularly where the Wall is very low, far less care with the Core's construction has been taken. (Figures 9,10) (Figure 10 is the upper extremity of Figure 9) The Wall at this point is at the top of a cliff and therefore does not necessitate a large Wall for defence, and is a few feet high. Less effort was taken with the Cores construction. In (Figure 10) you can see the erosion caused by the foot traffic of tourists. Little further damage can be done as the bedrock has been reached and is exposed already. This is the only location any such erosion was observed. This is in contract to locations such as (Figure 12) where foot traffic on the properly constructed Core, at present levels, seems to have no effect.

Most of the observed performances of the outer skin and the Core are very similar as they are both structural materials and systems of a similar nature built in exactly the same place. Therefore, performance comparisons are likewise similar. Nevertheless, Rammed Earth and Rubble are not brick and stone. Differences and similarities do clearly exist as indicated in the following observations.



Figure 9



Figure 10



Figure 11



Figure 12

Factors contributing to the failure of the exposed and unexposed Rammed Earth and Rubble Core: 1) Subsidence of the soil beneath the external walls. (At least 90% of failures seem to be due to this point alone). These can as previously stated, tear a section of the face from the Core, resulting in considerable damage, such as a significant reduction in the Core's width, and altering the angle of the Core's face from perpendicular to an inclined face more vulnerable to heavy rain events. 2) Rain erosion. 3) Human Foot traffic. 4) The removal of pavers atop the Wall allowing water penetration.

Factors contributing to the longevity of the exposed and unexposed Rammed Earth and Rubble Core: 1) Due to the Wall's builders' obsessive fastidiousness with draining water away from the top of the wall, as noted above for the outer skin. There is likewise no observed evidence of any failure of the Core due to water penetration on undisturbed sections of the Wall. 2) The squat dimensions of the Wall, its curves and bends and the protection provided by the outer skin for many centuries. 3) The Beijing area has a very dry winter with most rainfall falling during the summer. The exposed Core can therefore readily evaporate most rainfall. 4) War, vandalism, and seismic damage are largely absent. 5) The Wall is almost entirely built on ridgelines, normally rocky in nature, therefore ground or running water have not moistened the Core or the ground on which it is built. 6) The rocky ridges provide excellent foundations. 7) The fired bricks are never in contact with the natural ground. Therefore, they are unlikely wick water and pass it through to the Core. 8) Much vegetation was observed growing on the exposed Core. (Figure 7,12) The effect on the Core seems to one of preservation. This could be because the roots are stabilizing the Core and removing rainwater, the foliage, clearly sheltering the Core from harsh rain events common in the summer months, could be preventing rapid and significant erosion. 9) Fortunately animal infestation seems to not be a problem in the areas studies. Neither does wind erosion or farming. However mining and development could pose a threat in the near future.

4 SUMMARY AND CONCLUSIONS

Based upon the observations of this study, it seems that when the Rammed Earth and Rubble Core is exposed, it performs very well in comparison to a conventional Rammed earth wall of a comparative height. Unfortunately it was not possible in this study to determine the rate at which the Core is deteriorating. As the materials and workmanship are generally of a high quality and due to the considerable width of the Core, it is possible that in most places the Core is deteriorating at a very slow rate. In some observed locations, largely due to the fact that some of the Rubble Core is not laid in a fashion akin to Rammed Earth, but placed in loose earth, the Core will disintegrate quickly once the external walls fail.

Presumably due to the Cores greater width to height ratio, there is no evidence of cracking and very minimal leaning in the exposed Core despite some ground settlement. The only serious failures observed were due to complete subsidence of the ground. These subsidence events could be due to additional load from the Wall, undermining of the foundation, quite possibly as a result of numerous severe rain events, or perhaps a combination of these. However a far more rigorous study would be required to reliably understand these events.

It seems clear that due to the diversity of topography, the condition of the Wall and the vastly contrasting outer skin construction techniques of 100% stone, to almost 100% brick, performance conclusions of any future in-depth study need to be drawn on a location-to-location basis. However it may be possible to establish two basic models. The same will apply for conservation techniques and plans.

It is well known that the Great Wall in the Beijing area has proven to be an excellent and long lasting structure. Within the scope and focus of this studies observation, two primary contributing factors can be isolated.

1. The workmanship and materials were generally of a very high standard.
2. It is an excellent, location specific design, i.e. highly suited to the locations topography and climate. The author hypothesises that these two basic technique of construction, brick and stone, and (high quality only) Rammed Earth and Rubble, constructed as a combined unit, have probably, in the location studied, far exceeded the normal and expected lifespan of either technique were they utilised individually to build a Wall of the same dimensions.

It is the author's hope that these observations along with future in-depth study and analysis may prove helpful in conservation and/or restorative works.

Despite an age of approximately 500 years, the Beijing areas Great Wall, with its brickwork exterior, can look strikingly modern and strangely, has a familiar feel. Given that much of the wall with its defensive positions, and towers, resembles a European castle; it is not hard to understand why this is so.

Perhaps for those wishing to further the adoption of Earthen Buildings, particularly from a western perspective, the "conventional looking" and familiar, Beijing Great Wall, has much to offer.