

The Ancient Construction Materials and Methods: The Great Wall of China in Jinshanling as a Case Study

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Abstract: *The Jinshanling section of the Great Wall of China is a series of fortifications in northern China that was constructed for strategic military defenses. This section was first built in the beginning of the Ming Dynasty in AD 1368 and then underwent major construction, reconstruction and renovation during the late Ming Dynasty, approximately in AD 1569. The Jinshanling section is 10.5 km long, a very short section compared with the entire 21,200 km wall. The wall section is located in Luanping County, Hebei province, China. This research paper focuses on the construction methods and materials of the wall and the towers in the area. The research methodology includes site visits, knowledge acquisition of experts and 3D graphic modeling. This study reveals that the materials selected for the structure include rubbles and rammed earth, bricks, stones, timber, and mortar. The erection sequence of the wall and the towers was a bottom-up fashion using various ancient construction techniques, such as the fire-setting rock blasting techniques and the surveying techniques from the Sea Island Mathematical Manual.*

Keywords: *Great Wall of China in Jinshanling, Construction History, SOLIDWORKS, Ming Dynasty, Luanping County, Ancient Construction Materials and Methods*

I. INTRODUCTION

In recent years, the history of construction engineering has become an increasingly lucrative research topic, since its combination of historical data and modern construction principles has helped flesh out certain aspects of the past which would otherwise be challenging to historians. Additionally, this field of study preserves ancient construction techniques, and can possibly bring them forward for use in the modern civil engineering industry. Of particular significance in this research is the Great Wall of China, one of the most iconic landmarks of the country. The whole Wall is approximately 13,171 miles (21,197 km) long according to the State Administration of Cultural Heritage in China [1]; as such, this research required a narrowing of focus to a smaller section of the wall. Specifically, the focus of the research is upon the Jinshanling section, which consists of a 10.5-kilometer stretch between two of the 67 watch towers located at regular intervals throughout the wall. This part of the wall is located in Luanping County, roughly 155 km northeast of Beijing, China [2], and was first built in the beginning of the Ming Dynasty, ca. 1368; later on, during the Ming Dynasty ca. 1569, this section was significantly renovated, reconstructed, and expanded upon. This information was displayed on site. Also, the Chinese inscription on the bricks used to build the wall in eastern Jinshanling also verified the dynasty era. Because the Great Wall was constructed for military defense from Mongols attacking from the northern front, later Japanese pirates [3] and Manchus [4], fortifications were particularly reinforced

around the capital, such as the Badaling section in Beijing which is close to where the Jinshanling section is. Unlike the Badaling section, the Jinshanling section is not a major tourist site, which is beneficial because it has been better preserved over the years.

This research will focus on the construction methodologies employed during the Ming dynasty. Consultation with Yaohui Dong (the Vice Chairman of the China Great Wall Society and Director of the Management Committee of the Great Wall Protection Fund and an expert in the history of the Great Wall) during an interview in Beijing, China on May 23, 2015, has revealed that all standing structures from the Jinshanling sector are from the Ming dynasty. Any renovations would have occurred during and after this period. Since some Jinshanling sectors have not been significantly renovated for tourist attraction, parts of the wall are damaged enough that the authors could examine their constituency without intentionally damaging parts of the site. Therefore, the Great Wall of China in Jinshanling is suitable for a case study to examine the use of digital technology to recreate ancient construction materials and methods.

II. OBJECTIVES, SCOPE AND SIGNIFICANCE OF THE STUDY

The objectives involved in this study included acquiring, displaying, and discussing the ancient materials and methods of construction of the Great Wall of China. The scope of the study focuses on the Jinshanling section of the Great Wall during the period from the new construction work in the Ming Dynasty (1368) to the major

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renovations in the late Ming Dynasty (approximately 1569). The study mainly focuses on the towers and the wall connecting them (Fig. 1). There are two types of towers, those supported by bricks and arches (a configuration influenced by ancient Roman architecture) in the interior of the first floor (Fig. 2), and those mainly supported by wood columns in the interior of the first floor (Fig. 3). While there are architectural variances, for example, different numbers of entrances and windows or different locations for the arches or wood columns, within each type the material selection and erection sequence are similar. The authors therefore divided the towers into two categories. The significance of the study included the extraction of the construction materials and methods to be modeled using SOLIDWORKS. The authors hope this paper would contribute to and potentially engender 3D modeling work on other sections of the Great Wall of China and other ancient structures. The 3D modeling is also useful for showing missing, or hidden components of ancient structures, which can be essential for students seeking to understand the construction sequence without having to travel to the site directly.



FIGURE I
THE WALL

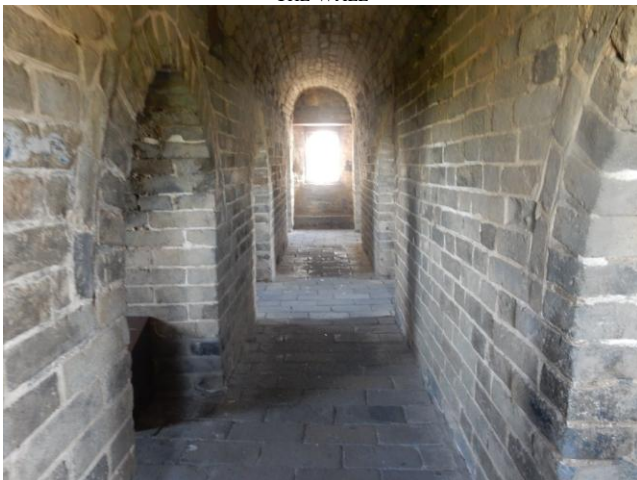


FIGURE II
BRICKS AND ARCHES SUPPORTED TOWER



FIGURE III
WOOD COLUMNS TOWER

III. LITERATURE REVIEW

Given the scale of the Great Wall compared to the current state of engineering research, literature similar to this paper is limited. Literatures written in English on the Great Wall described the overall history of the wall included Geil [5], Lovell [6], and general construction materials and methods in different dynasties, including the Ming Dynasty by Luo, Zhao [7] and Luo et al. [8]. No literature on the systematic construction, or construction sequence, is known for the Jinshanling area specifically, especially not with regards to 3D modeling. However, there are still literature reviews that are helpful to develop this study. This includes Dark's conference paper [9] describing the structure performance and materials in the Jinshanling and surrounding areas. An archaeological report, written by Zheng [10], shows the onsite measurements of the towers and the wall in Jinshanling. Additional data related to the ancient surveying and excavation methods in China is also known from Swetz, Liu [11], Needham and Ho [12]; the authors of this study believe that these methods were likely used on the Great Wall in Jinshanling.

IV. METHODOLOGY

The methodology of the study included data acquisition, construction of the structure using 3D modeling and creation of the construction plans (sequence of construction and material description).

The data (inputs) used for the outputs is derived from the qualitative and quantitative measurements taken from onsite visits, literature reviews and the expert knowledge. For instance, the first author conducted onsite inspections and took measurements of individual wall components such as the bricks, foundation stones and other materials. As stated before, Zheng's report provided the overall dimensions of the structures from their onsite measurements. Dark's conference paper described the materials that were used to build the structure in the surrounding area, it specifically mentioned sticky-rice lime

mortar. In addition, the authors have visited and investigated the Great Wall of China and their expertise to simulate the reconstruction of the Great Wall.

The outputs included the reconstructed 3D modeling in both rendered images and animation, sequence of construction plan in a table form, and construction material description plan in a table form. After the data collection, the SOLIDWORKS 3D CAD design software was used to rebuild the monument in a bottom-up fashion, meaning that the individual parts of the structures and the wall were first created, such as foundation stones and bricks, and then assembled those parts to reconstruct the Great Wall. The inputs were incorporated into the SOLIDWORKS modeling, such as overall and individual dimensions and material textures from onsite photos, as mentioned above. As stated in the previous section, SOLIDWORKS was selected for the study because it has the ability to display and visualize the missing or hidden components of the structure.

V. CONSTRUCTION MATERIALS

The discussion of the construction material selection is divided into three sections: the material selection of the wall, the material selection of the wood column towers, and the material selection of the bricks and arches towers.

A. Material Selection of the Wall

The material selection of the wall is divided into three main components: the outer layer, the inner layer (inner core) of the wall, and the walkway. The walkway includes the battlement, the wall, and other features such as stone/sanitary holes, drainage holes, barrier wall (if applicable), stairs, and others. The outer layer of the wall was built using foundation stones and fire kiln bricks (Fig. 4). Based on the visual inspection from the onsite visits by the authors and personal communication with another investigator (D. Dark, personal communication, 2015), the foundation stones were likely made of conglomerate. The inner layer consisted of rubble, rammed earth, and possibly small rubble bound by mortar used as adhesive and filler (Fig. 5). The rammed earth originated onsite, and is most likely what is known as cinnamon soil in Chinese (褐土, Hetu in pinyin) with the soil texture of doras or loam (壤土, Rangtu in pinyin). The soil data was extracted from China's Forest Resource Inventory with the help of specialists from the Ecology Center for Earth System Science of Tsinghua University (C. Huang and J. Yang, personal communication, June 2015). Gray brick pavers were used to finish the walkway and bricks were used to build the battlement and wall. Fig. 6 show that some parts of the stone/sanitary holes were from granite stones in the eastern part of Jinshanling, Mortar was used as adhesive for all the material selection. Table 1 summarizes the material selection for the wall.



FIGURE IV
MATERIAL SELECTION FOR THE FOUNDATION OF THE WALL



FIGURE V
MATERIAL SELECTION FOR THE INNER CORE OF THE WALL



FIGURE VI
MATERIAL SELECTION (BRICKS AND GRANITE STONE) FOR THE
STONE/SANITARY HOLE OF THE WALL

TABLE I
Material Selection of the Wall

Component of the Wall	Material Selection	Material Descriptions
Outer wall	<ul style="list-style-type: none"> Use of foundation stone and fire kiln bricks with mortar 	<ul style="list-style-type: none"> Gray conglomerate foundation stones Fire kiln bricks Mortar may contain small amount of sticky rice paste
Inner (core) wall	<ul style="list-style-type: none"> Use of rubble Use of rammed earth and possibly small rubble bound with mortar used as adhesive and filler 	<ul style="list-style-type: none"> Earth came from cinnamon soil with doras or loam soil texture Rubble likely came from cinnamon soil with doras or loam soil texture
Battlement, wall and barrier wall (if applicable)	<ul style="list-style-type: none"> Use of bricks and mortar 	<ul style="list-style-type: none"> Fire kiln bricks
Drainage system and other openings	<ul style="list-style-type: none"> Use of bricks and mortar Use of stones in some stone/sanitary holes 	<ul style="list-style-type: none"> Fire kiln bricks Some holes were supported by granite stones
Pavers	<ul style="list-style-type: none"> Use of bricks and mortar 	<ul style="list-style-type: none"> Gray colored fire kiln bricks *Possibly use of cobblestone during the new construction



FIGURE VII
Monolithic stone base and plinth for a wood column



FIGURE VIII
Material selection for components of a bricks and arches tower (mini tower entrance)

TABLE II
Material Selection of the Wood Column Tower

Component of the Wood Column Tower	Material Selection	Material Dimensions
Outer layer of the base	<ul style="list-style-type: none"> Use of foundation stones and fire kiln bricks with mortar 	<ul style="list-style-type: none"> Gray conglomerate foundation stones Fire kiln bricks Mortar may contain small amount of sticky rice paste
Inner (core) of the base	<ul style="list-style-type: none"> Use of rubble Use of rammed earth and possibly small rubble bound by mortar used as adhesive and filler 	<ul style="list-style-type: none"> Earth came from cinnamon soil with doras or loam soil texture Rubble likely came from cinnamon soil with doras or loam soil texture
Wood columns (first floor)	<ul style="list-style-type: none"> Use of timber columns Use of stone base and plinths (monolithic) 	<ul style="list-style-type: none"> Not available
Exterior Wall (first floor)	<ul style="list-style-type: none"> Use of bricks with mortar and timber columns * Some towers did not have wood columns embedded in the exterior wall 	<ul style="list-style-type: none"> Fire kiln bricks
Door and windows (first floor)	<ul style="list-style-type: none"> Use of timber for doors and windows frames stones and/or bricks with mortar for entrance steps (thresholds) and windowsills Use of timber or iron for the actual doors and windows 	<ul style="list-style-type: none"> Not available
Stairs and opening (to the second floor)	<ul style="list-style-type: none"> Use of stones and/or bricks with mortar Use of timber for the opening 	<ul style="list-style-type: none"> Fire kiln bricks if used
Battlement (second floor)	<ul style="list-style-type: none"> Use of bricks Use of stones for windowsills and drainage system 	<ul style="list-style-type: none"> Fire kiln bricks
Finishing	<ul style="list-style-type: none"> Use of brick pavers Use of timber for windows and doors 	<ul style="list-style-type: none"> Gray fire kiln bricks

B. Material Selection of the Wood Column Towers

The materials of the base of the wood column towers (from foundation to the first floor) is parallel to the wall, where rubble and rammed earth were selected for the inner core of the base, and foundation stones and bricks were selected for the outer core of the base. The first floor of a

typical wood column tower (Fig. 3) consisted of wood columns in the center and sides of the building (exterior wall). The wood columns on the sides of the building were half-wrapped with bricks and supported by the plinth and base. The plinth and base are made from stone and are monolithic, as shown in Figure 7. Note that some towers that do not have any wood columns on the sides of the building. Based on observations of the renovated towers, the window frames, doorframes, and other frames were most likely made from wood while the actual doors and windows were likely made from either wood or iron. By contrast, the windowsills and thresholds were constructed from bricks and/or stones. The wood columns were placed to support the second floor. Most likely, the second floor was to be built atop the first floor with timber boards and brick pavers. There is no evidence to suggest that a smaller tower (or tent) was built atop the second floor. If evidence of a smaller tower arises in the future, then the authors will add to their research database. Bricks were selected for the battlement on the second floor. The windowsills on the battlement were most likely made from stone. Storm water drains, made from carved stone, were included on the sides of the second floor. Table 2 summarizes the material selections of the wood column designed tower.

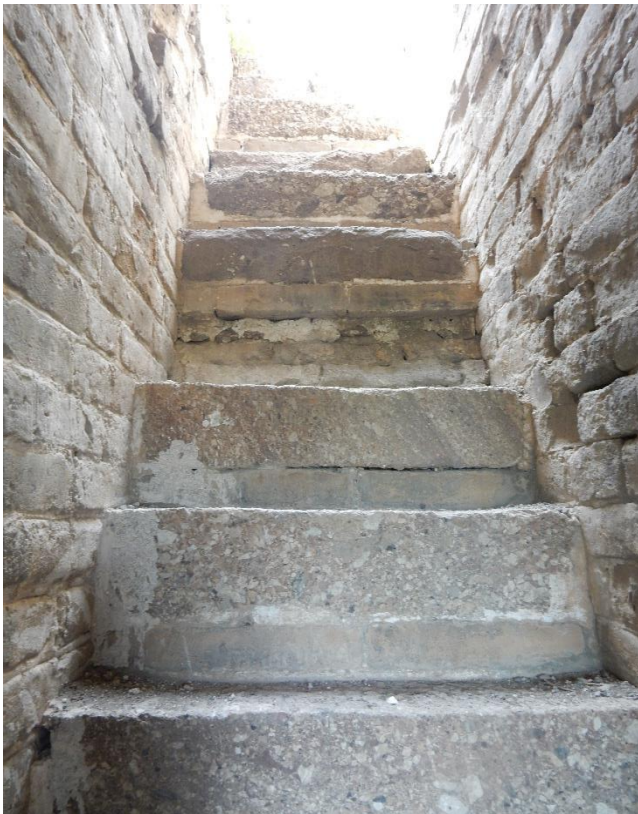


FIGURE IX

Material selection for components of a bricks and arches tower (stair)

C. Material Selection of the Bricks and Arches Towers

The first floor of a typical bricks and arches tower consisted of fire kiln bricks used for the interior walls, vaults, and arches (Fig. 2). The design of the vaults and

arches (configuration of the brickwork) was influenced by an ancient Roman design. The side of the tower (exterior wall) was also constructed from fire kiln bricks. It is believed that carved stones were used to reinforce the entrance and exit of some towers (thresholds, keystones, voussoirs, imposts, and piers). Door, window and other frames were most likely made from timber and the thresholds from stone, like the recently renovated entrance (Fig. 8). Some thresholds and windowsills were made from bricks alone to reduce the weight on the mini tower. Stairs leading to the second floor were made of stone in some towers (Fig. 9) and from bricks in other towers. A mini tower (or tent) was built on the second floor using timber and bricks in a way similar to the reconstruction of a mini tower in middle Jinshanling (Fig. 10). The existing stone plinths on the second floor are evidence that a mini tower was constructed. Smaller timbers (approximately \varnothing 31.75 cm, as shown in Table 4) were used for the columns and posts for the mini tower. Timber was also used for the beams in the roof of the mini tower. For the battlement on the second floor and the exterior wall of the mini tower, brickworks were selected. Based on the recently renovated mini towers, ceramic roofing tiles were probably used for roofing. Storm water drains (from carved stone) were located on the sides of the second floor (Fig. 11). Table 3 summarizes the material selection for the bricks and arches designed tower.



FIGURE X

Material selection for components of a bricks and arches tower (mini tower on the second floor)



FIGURE XI

Material selection for components of a bricks and arches tower (drainage on the second floor)

TABLE II
Material of Bricks and Arches Tower

Component of the Bricks and Arches Tower	Material Selection	Material Descriptions
Outer layer of the base	<ul style="list-style-type: none"> Use of foundation stones and fire kiln bricks with mortar 	<ul style="list-style-type: none"> Gray conglomerate foundation stones Fire kiln bricks Mortar may contain small amount of sticky rice paste
Inner (core) of the base	<ul style="list-style-type: none"> Use of rubble Use of rammed earth and probably small rubble with mortar used as adhesive and filler (gap between rubble) 	<ul style="list-style-type: none"> Earth came from cinnamon soil with doras or loam soil texture Rubble likely came from cinnamon soil with doras or loam soil texture
Interior wall (first floor)	<ul style="list-style-type: none"> Use of bricks and mortar 	<ul style="list-style-type: none"> Fire kiln bricks
Exterior wall (first floor)	<ul style="list-style-type: none"> Use of bricks and mortar 	<ul style="list-style-type: none"> Fire kiln bricks
Doors and windows (first floor)	<ul style="list-style-type: none"> Use of timber for doors and window frames Use of stones and/or bricks with mortar for entrance steps (thresholds) and windowsills Use of timber or iron for the actual doors Use of timber for the windows 	<ul style="list-style-type: none"> Fire kiln bricks if used
Stairs (to the second floor)	<ul style="list-style-type: none"> Use of stones and/or bricks with mortar 	<ul style="list-style-type: none"> Fire kiln bricks if used
Ceiling (first floor)	<ul style="list-style-type: none"> Use of bricks for arches and vaults 	<ul style="list-style-type: none"> Fire kiln bricks if used
Wood column posts and roof (second floor)	<ul style="list-style-type: none"> Use of timber 	<ul style="list-style-type: none"> Not available
Wall Structure (second floor)	<ul style="list-style-type: none"> Use of bricks with mortar 	<ul style="list-style-type: none"> Fire kiln bricks
Doors and windows (second floor)	<ul style="list-style-type: none"> Use of timber for doors and windows frames Use of stones and/or bricks with mortar for entrance steps (thresholds) and windowsills Use of timber for the actual doors and windows 	<ul style="list-style-type: none"> Fire kiln bricks if used

Roof structure (second floor)	<ul style="list-style-type: none"> Use of timbers for posts and beams Use of roofing tiles 	<ul style="list-style-type: none"> Ceramic tiles
Battlement (second floor)	<ul style="list-style-type: none"> Use of bricks and mortar Use of stone (windowsills) 	<ul style="list-style-type: none"> Fire kiln bricks
Finishing	<ul style="list-style-type: none"> Use of brick pavers for floor finishing Use of timber for doors and windows 	<ul style="list-style-type: none"> Gray fire kiln bricks

Table 4 summarizes the material dimensions taken onsite in different areas of Jinshanling.

TABLE IV
Material Dimensions in Jinshanling

Material	Location	Size (Onsite Raw Data)	Size (cm)
Paver	Little Jinshan Tower (second floor)	15" by 15" (Length × Width)	38.1 × 38.1 (L × W)
Paver	Big Arc Tower	14" by 14" by 3.5" (Length × Width × Depth)	35.6 × 35.6 × 8.9 (L × W × D)
Paver	Wall between Little Jinshan and Large Jinshan Tower	12" by 8"	30.5 × 20.3 (L × W)
Paver	Wall between Yaogou and Unnamed Building	15" by 6"	38.1 × 15.2 (L × W)
Paver	Wall between Little Arc and Big Arc Tower	15" by 7.5" by 4"	38.1 × 19.05 × 10.16 (L × W × D)
Brick	Big Arc Tower	16" by 8" by 4"	40.6 × 20.3 × 10.16 (L × W × D)
Brick	Wall between Little Jinshan and Large Jinshan Tower	14.5" by 3.75"	36.8 × 9.5 (L × D)
Brick	Little Jinshan Tower (second floor)	14.5" by 7.2" by 3.5"	36.8 × 18.3 × 8.9 (L × W × D)
Wood Log	Shazi	19.5" Diameter	∅ 49.5
Wood Log	General (second floor)	12.5" Diameter	∅ 31.75
Wood Log	Corner	20" Diameter	∅ 50.8
Wood Log	Unnamed (eastern Jinshanling)	19.5" Diameter	∅ 49.5
Wood Log	Building with three holes	19" Diameter	∅ 48.3

VI. CONSTRUCTION METHODS OF THE GREAT WALL OF CHINA IN JINSHANLING

This section of the study is divided into two subsections, the erection sequence of the wall and the

erection sequence of the towers. The wall and the towers were built separately. Figure 12 shows the mortar stain after the wall had deteriorated, and it shows evidence that the material of the tower and that of the wall are only integrated by mortar. The construction of the wall and of the towers was therefore separate.



FIGURE XII

Evidence (mortar stain) showing separate construction of tower and wall

A. The Erection Sequence of the Wall

The first stage of the construction process, the pre-planning stage, began with the surveying of the worksite. The ancient Chinese were thought to have relied upon the Sea Island Mathematical Manual for this part of the process [11], relying on pre-calculated triangular and rectangular dimensions such as those for the cut/fill of the foundation, the base of the structure, and the floor plans, as well as the shape of the natural terrain. The authors also believe that the wall was built in sections, as shown in Figure 13, which were then connected together. This construction process would allow for better controlling of the global and local geometry of the structure compared to unidirectional horizontal construction (from the starting to the ending point).

Previous research [13] has shown that the structure was mostly constructed directly upon the land natural slope, on a bedrock or rubble foundation. To construct the wall section, the workers first cleared the site of weeds, rocks, and other debris, and then began excavation with the intent of cutting the bedrock into a stair-like formation. This allowed them to place foundation materials such as rubble, stone, and brick horizontally while still enabling them to build a slanted wall later on. For areas where the foundation could not be excavated, where the ground-level rock and earth was too hard to break for example, backfilled rubble could be used to level the foundation site as well as the surface of the foundation itself, allowing the foundation stones to be placed horizontally. The workers may have built the foundation using fire-setting [12] among other ancient methods. The authors compiled four options for excavation known in antiquity:

- Manual excavation, using hammers to break off pieces of stone and cut the foundation pieces down to their desired size;
- Fire-setting, raising the temperature of the stone and then cooling it with water or vinegar to fracture it via thermal shock [12];
- Crack expansion, a cold-season method during which cracks or holes made in the stone were filled with water, which expanded and pushed the pieces apart; and
- Explosive fracture, or inserting gunpowder into drilled holes and lighting the gunpowder to break the rock into smaller fragments – an early form of which being “plug-shooting”, involving 2”-diameter holes, 3 to 4 feet deep, filled with gunpowder and sealed with wooden bungs (Needham & Ho, (Note 12) pp. 536-537).

With respect to crack expansion, David Dark, the Technical Director at Infinity Design & Engineering in China, has more than 25 years of construction experience and has been to the Jinshanling section of the Great Wall numerous times; among the knowledge he provided, he specifically describe that holes were drilled into the rock along any existing fracture lines. In the wintertime, the workers would fill the holes with water. The water would later freeze, forming ice that would expand and break up the surrounding rock. The process would then be repeated until the desired effect was accomplished. This methodology would have worked because it took advantage of the expansion and contraction of the freeze/thaw cycle, and thus maximized the utility of the lower temperatures at night and the warmer temperatures during the day. Liquid water would seep into small cracks during the day and the rock would later split apart due to the expansion of the freezing water at night. This freezing portion of this method would work best at night, when the temperature dropped to or below freezing; the daytime temperatures, meanwhile, were more conducive to thawing the frozen water. Spring and autumn weather were therefore the most feasible seasons for this practice. However, there were six weeks in the winter when temperatures were low enough that the water would stay frozen. The ice was therefore melted back into liquid water manually, via fire setting (D. Dark, personal communication, July 2015).

While all four of these methods were likely used to break up the harder rocks at the work site, it is not known which was used the most often. Most likely, which method was used at any given time would have been based on which was most efficient, although explosive blasting was probably used only sparingly due to gunpowder being a scarce and valuable wartime resource at the time.

Fig. 13 shows the overall construction sequence of the wall as constructed in Dassault Systèmes SOLIDWORKS 2014-2015 and rendered using PhotoView 360. For the

purpose of this paper, the authors consider any component below the pavers of the walkway as the substructure and any component at or above the pavers as the superstructure. With the foundation prepared, the workers could now begin construction on the wall proper, beginning by piling rubble and rammed earth in the middle (inner) wall layer and facing it with foundation stones and bricks on both sides (Fig. 13 I). The stones and bricks had to be stacked in a stable, level configuration, and the bricks in particular were viable for this purpose because they could be arranged in a relatively flat Flemish bonding formation, compared to the more haphazard size ranges of the rubble pieces. Large rubble was stacked first, and the gaps then filled with the smaller rubble, rammed earth, and mortar (Fig. 13 II). The inner and outer wall layers were then integrated with key-in feature, as shown in Figs. 13 III and IV; note that there were more bricks (for the outer core) and less rubble (for the inner core) used for this region than in the previous steps of the sequence as shown in Figs. 13 I and II. The load-bearing portion of the wall was built to approximately five meters by repeating the previous steps (including an additional key-in feature), shown in Figs. 13 V to VIII; at higher elevations, wooden scaffolding would have been employed for safety purposes. After this, workers would then build the battlement on the north side of the wall, and the guard-wall on the south, both of which were angled to the slope of the terrain rather than the foundation and brickwork. Other features such as the stone holes on the north side, the peepholes (or arrow holes) and the water drain holes on the south side were also included at this time. Finally, two or more paver layers were added for the walkway along with a water guide for the drain holes (Fig. 13 IX). The overall sequence of construction was also rendered in the form of a video animation, which was saved into .avi file. The file could be played using any Window Media Player or Movie & TV app on Windows 10 Home Edition, as shown in Figure 14. The resultant wall dimensions varied depending on the location of each build site, and the various measurements can be found in Zheng’s archaeological report [10]. The dimensions used in the modeling of the structure were from Unnamed Building 10, 11, and the wall connecting it in western Jinshanling. The overall dimensions of the focused structure were summarized in Table 5 and incorporated in SOLIDWORKS. Table 6 summarizes the construction sequence of the wall.

TABLE VI
Construction Erection Process of the Wall

Step	Construction Phase	Sequence	Construction Methodology
I	Pre-plan and plan	Survey	<ul style="list-style-type: none"> The Sea Island Mathematical Manual Surveying used every phase of the construction
IIA	Substructure (base)	Excavation	<ul style="list-style-type: none"> Manual, fire-setting and other methods used cut to bedrock
IIB		Foundation	<ul style="list-style-type: none"> Stair-like shape bedrock and/or rubble used to level
IIIA		Outer wall	<ul style="list-style-type: none"> Foundation stones to fire kiln bricks stacked using bottom-up fashion Wood scaffolding used for safety reasons and for building at higher height
IIIB		Inner (core) wall	<ul style="list-style-type: none"> Rubble stacked with rammed earth and mortar in bottom-up fashion Wood scaffolding used for safety reasons and for building at higher height
IVA	Superstructure (walkway)	Battlement, wall, and barrier wall (if applicable)	<ul style="list-style-type: none"> Brickwork constructed in bottom-up fashion at an angle following the slope of the terrain Wood scaffolding used for safety reasons and for building at higher height
IVB		Drainage system and other openings	<ul style="list-style-type: none"> Brickwork and stones with mortar used to correct slope to drain
IVC		Pavers	<ul style="list-style-type: none"> Bricks and mortar used to correct slope Second layer overlapped the first layer’s mortar point

TABLE V
Dimensions (inputs) of the 3D modeling

Structure	Overall dimensions in meters (Length x Width x Height) [10][13]
Unnamed Building 10 (wood columns supported tower)	11.90 x 10.40 x 11.50
Unnamed Building 11 (bricks supported tower)	10.80 x 10.00 x 11.00
Wall connecting the towers	115.00 x 4.90 x 5.00



FIGURE XIV
Sequence of Construction of the Great Wall animation

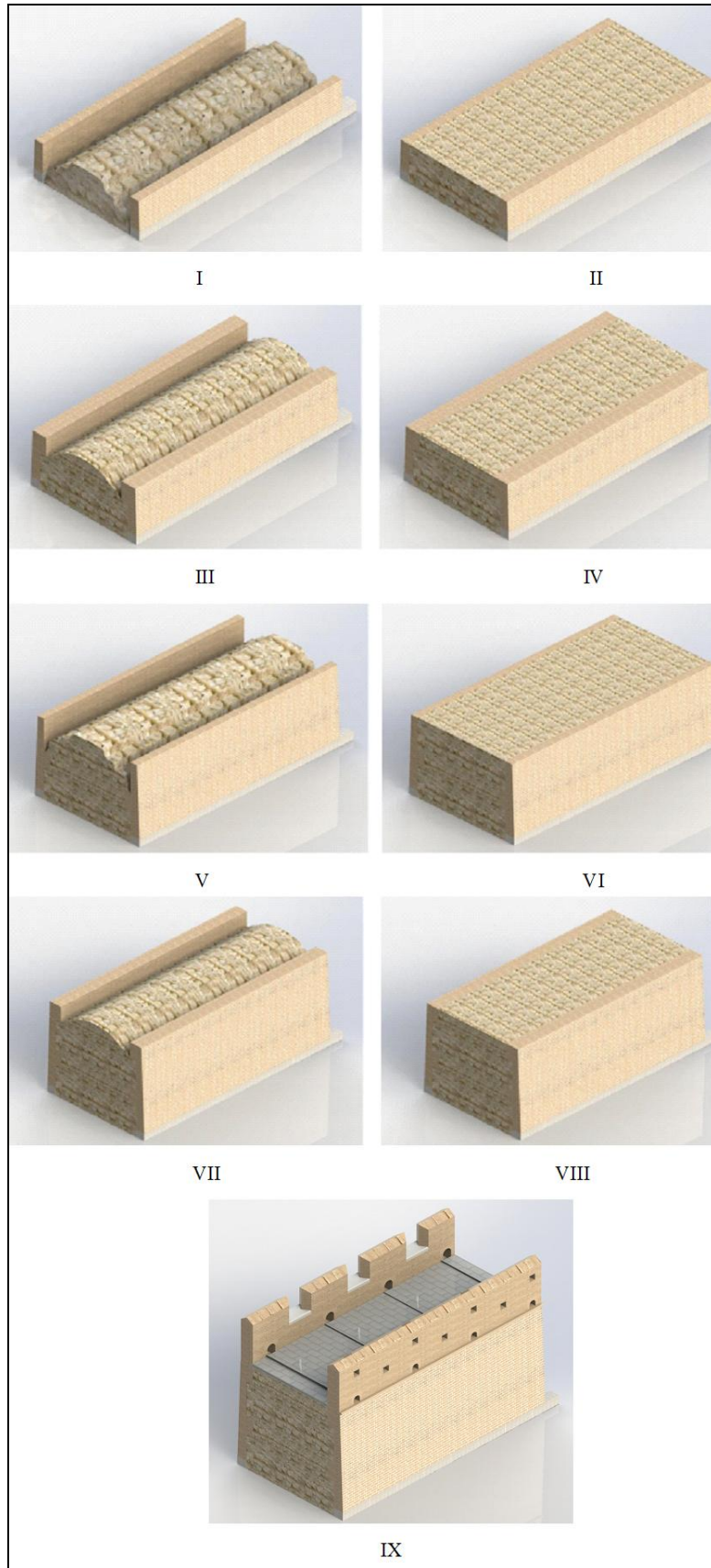


FIGURE XIII
Erection process of the wall using SOLIDWORKS

B. The Erection Sequence of the Towers

As noted, the two types of towers of the Jinshanling section of the Great Wall are wood column and bricks and arches supported towers. The design of these tower types varies in terms of architectural, structural, and defensive strategy, e.g. domes on some of the bricks and arches towers, extra posts outside the brick walls, etc. Similar to the wall, the authors consider any component below the pavers on the first floor of the towers as the substructure and any component at or above the pavers as the superstructure. The underlying material selection and construction method of each tower, however, is relatively consistent. For the Jinshanling sector specifically, the foundation and the base were constructed in a similar fashion to the wall itself, with rubble, rammed earth, and mortar stacked up within a rectangular area marked by foundation stones on opposite proposed corners. The tower itself was built from rubble and rammed earth faced by foundation stones and bricks, stacked in a bottom-up fashion to approximately five meters.

The wood column towers were constructed differently (Fig. 15 II). The stone plinths and timber columns were the first parts of the structure to be erected as a framework, and the bricks would be stacked around the columns to flesh out the tower (exterior wall). This method is evidenced by the fact that the brickwork appears to wrap around the columns at the corners of the structure onsite and it is shown in Fig. 15 I. After the first floor walls and columns were erected, wooden beams, boarding and stairs were installed for workers to reach the second floor and begin constructing the battlement there. Then, one or more layers of brick pavers were used to finish the first and second floor layers, also windows and door were installed at the edges of the floors. It is likely that the wood column towers did not have a mini-tower or tent, because the timber columns would not have had the compressive strength to support the mini-tower, unlike the bricks and arches towers.

For the bricks and arches towers (Fig. 16 III), the interior brick columns were stacked either before or during the erection sequence of the exterior wall. Arches and vaults were constructed to support the structure once the walls were raised to the desired height (Fig. 16 I); these components were similar to the ones seen in Roman construction and required framework for assembly. Stairs were also constructed at the same time, leading up to the second floor, and wooden scaffolding was likely included as well, for safety reasons and to build at a higher altitude. The plinths and timber columns were placed for the second floor walls before the mini-tower walls were built, and a few towers also have additional timber columns outside of the wall bearing the mini-tower (Fig. 16 II). Bricks were then stacked to fill out the walls of the second floor as with the first one. The roof was then erected first with timber posts and beams, and then ceramic tiles. Battlements were constructed around the second floor tower. Finally, the floors were finished with at least one or more layers of brick pavers, and windows and doors were installed on the tower floors.

As before, the overall dimensions of each tower depended on the location, defensive purposes, and architectural characteristics among other variables. The onsite measurements for individual towers can be found in Zheng’s archaeological report [10]. Table 7 summarizes the construction method of the towers (both wood column supported towers and bricks & arches supported towers).

TABLE VII
Construction Erection Process of the Tower

Step	Construction Phase	Sequence	Construction Methodology
I	Pre-Plan and plan	Surveying	<ul style="list-style-type: none"> The Sea Island Mathematical Manual Surveying used every phase of the construction
IIA	Substructure (base)	Excavation	<ul style="list-style-type: none"> Manual, fire-setting and other methods used cut to bedrock
IIB		Foundation	<ul style="list-style-type: none"> Stair-like shape bedrock and/or rubble used to level
IIIA		Outer layer of the base	<ul style="list-style-type: none"> Foundation stone to fire kiln bricks (bottom-up fashion) Wood scaffolding used
IIIB		Inner (core) of the base	<ul style="list-style-type: none"> Stacked rubble, rammed earth, and possibly small rubble with mortar used as adhesive and filler for the gaps in the rubble Wood scaffolding used
IVA-1	Superstructure (floor structure of wood column towers)	Wood columns	<ul style="list-style-type: none"> Timber columns with stone plinths erected in the center and corners and sides of the floor plan Use of timber beams and broads for ceiling Wood scaffolding used
IVA-2		Wall	<ul style="list-style-type: none"> Bricks and mortar used (bottom-up) Wood scaffolding used
IVA-3		Door openings and window openings and other openings	<ul style="list-style-type: none"> Door and window openings built using framework

TABLE VII
Continued

Step	Construction Phase	Sequence	Construction Methodology
IVA-4		Stairs and opening (second floor)	<ul style="list-style-type: none"> Stones and/or bricks with mortar stacked in bottom-up fashion Wood scaffolding used
IVA-5		Battlement (second floor)	<ul style="list-style-type: none"> Bricks stacked Stone placed for windowsills and drainage system
IVA-6		Finishing	<ul style="list-style-type: none"> Pavers, actual doors, actual windows, and other miscellaneous items installed
IVB-1	Superstructure (floor structure of bricks and arches towers)	Interior Wall	<ul style="list-style-type: none"> Bricks and mortar placed in bottom-up fashion *Roman arch, vault, and dome design used Wood framework used
IVB-2		Exterior Wall	<ul style="list-style-type: none"> Bricks and mortar stacked (bottom-up) Wood scaffolding used
IVB-3		Doors and windows and other openings	<ul style="list-style-type: none"> Stones and/or bricks with mortar used *Timber used for the doors and windows in some towers Wood framework used
IVB-4		Stairs	<ul style="list-style-type: none"> Stones and/or bricks with mortar used Wood scaffolding used
IVB-5	Superstructure (mini tower)	Wood Column Posts (Second Floor)	<ul style="list-style-type: none"> Timber posts used to support roof configuration Wood scaffolding used
IVB-5.1		Wall Structure (Second Floor)	<ul style="list-style-type: none"> Bricks stacked for the wall (bottom-up) Wood scaffolding used

TABLE VII
Continued

Step	Construction Phase	Sequence	Construction Methodology
IVB-5.2		Door openings and window openings (second floor)	<ul style="list-style-type: none"> Window openings and door openings built using framework Bricks stacked in a bottom-up fashion Wood scaffolding used
IVB-5.3		Roof Structure	<ul style="list-style-type: none"> Timber beams erected for roof configuration Timber posts erected outside the tent wall (if applicable) Ceramic roofing tiles installed Wood scaffolding used
IVB-6		Battlement	<ul style="list-style-type: none"> Bricks with mortar placed in bottom-up fashion Stone used windowsills and drainage system
IVB-7		Finishing	<ul style="list-style-type: none"> Pavers, actual doors, windows, and other miscellaneous items installed

VII. DISCUSSION

The construction sequence plan described in this paper is based on the authors' own construction experience and on the most logical way to construct it. There are alternative sequences for constructing the structure, but not all of them may be logical and so some could decrease productivity. However, the Chinese would have had to use an alternative sequence in situations where other variables were factors, for instance, lack of workers or material resources. Conversely, if they had more workers and more resources, construction sequences could have been combined.

Next, it was hard to identify whether some repairs were recent or from the time of the Ming Dynasty. Because the authors could not clearly identify some recent repairs on the Great Wall, they used their subjective judgment to describe the construction materials and methods used during the Ming Dynasty in this study.

There was evidence of the key-in feature in the eastern section of Jinshanling's wall where pure rammed earth was used for the inner core of the wall, as shown in the PowerPoint slides [14]. Based on logic, the authors believe that the key-in feature was likely included during renovation of the wall as well as reconstruction or expansion during later time periods. The key-in feature was also likely to have been used in new construction, because the key-in feature would have helped minimize the likelihood that the outer core of the wall would slide off from the inner core in the case of earthquake, and other natural disturbance. If later evidence shows that the key-in feature was not used in the wall connecting the Unnamed Building 10 to Unnamed Building 11, the model could be adjusted and updated accordingly. Lastly, there is currently no evidence that key-in feature was used on the base of the towers, though this assertion may be subject to change following future studies.

VIII. CONCLUSIONS

In this research, the Great Wall of China in Jinshanling was investigated as a case study to determine the ancient construction materials and methods. While there were variances (such as architectural, defense design, location, and others), for each type of tower, the material selections for the structure (both the wall and the towers) were the same, consisting mainly of rubble and rammed earth, bricks, stones, timber, and mortar. The erection sequence was similar for the substructure of both types of tower: the base of the structure was filled with rubble and rammed earth as the inner core of the structure and foundation stones and bricks as the outer layer of the structure. Some variance included the material selection for the stairs; stone stairs were used in most towers, but in some of them, brick stairs were used. Moreover, some towers used stone for the entrance, exit, arch, and window openings, while others used bricks. This may reflect the materials available at the time of construction. The knowledge base was then embedded into a 3D modeling system created using SOLIDWORKS, which displays a state-of-the-art visualization schema based on the sequence of construction and the material selection for each component of the structure. This objective was achieved via rendered 3D static images and animation. Furthermore, tables of construction sequence and material description were also created using the database from onsite visits, literature search and knowledge acquisition from the experts. The advantage of the construction sequence and material description tables presented here is that they are simpler to comprehend compared to descriptions in a novel form. As such, this paper is expected to open up more research on the construction materials and methods of ancient structures.

IV. FUTURE STUDIES

For future recommendations and studies, more sample data collection, such as dimensions of the columns, are needed to fully analyze and support the authors' results on the construction material selections and methodologies of the Great Wall of China in Jinshanling. Also, a more advanced state of the art display methodology, such as Virtual Reality using Oculus Rift headset, can be employed to demonstrate the construction methods of this important monument. Finally, knowledge acquisition from experts in other specializations within civil engineering, such as surveying, structural, hydraulic/water resources, transportation and others, could also be obtained and utilized to improve the results in this paper.

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