Maintenance Concept of the Rammed Earth Finishing of the Historic City Wall of Pingyao Shanxi Province, PR China-based on re-evaluation of mock-ups in 2007

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ABSTRACT: One of the remarkable characteristics of the Ancient Pingyao City Wall, which has been listed as a Cultural World Heritage Site in 1997, is the internal rammed earth finishing. Based on laboratory tests, especially consolidation tests with various types of limes, it has been found out the loess soil, the main construction material, needs to be consolidated with lime mixture of air lime and hydraulic lime to reach a level of water and frost resistance. “Earth on Earth” was considered as sustainable and traditional concept to restore and maintain the earthen finishing. Two “earth on earth” options have been developed during the period of research framework in 2006-2007. Option 1 was to ram a new support layer with lime stabilized local soil. Hydraulic lime was added to improve the setting and hardening. Option 2 was to build a new adobe masonry but plastered with lime modified earth mortars as protective layer. Based on quality examination and visual evaluation in 2011, option 1 was chosen as the standard maintenance measurement to restore the existing wall. This technique has been more or less successfully implemented from 2012. Subsequent visual inspections have been done by authors in Sommer 2015 and 2018 not only to the restored areas, but also to mock-ups done in 2007. It has been found that the lime-earth plaster has functioned surprisingly well, it has protected adobe from erosion and deterioration. It is therefore proposed that ramming is an effective and also traditional method to protect the rammed earth walls while retaining the internal compaction, but a protective lime-earth plaster to rammed wall surface could be a sustainable solution to maintain the entire wall with very reasonable costs to avoid major restoration works in the future. This lime-earth plaster works as sacrificial layer to protect the entire surface against erosion through regulating the moisture and thermal balance under Pingyao climate.

KEY WORDS: Pingyao, Rammed earth wall, maintenance, lime earth plaster, adobe

1 Introduction

One of the remarkable authentic characteristics of the Ancient Pingyao City Wall is the internal rammed earth finishing (Figure 1) where the exterior was masonried subsequently around 1575 using natural stones, grey bricks and lime mortar[1]. The Pingyao City Wall stands for centuries not only due to the construction technique, extreme dry climate, but also through repeated reconstruction in the history and maintenance. Under national and international conservation principles, continuous maintenance with traditional technique is always encouraged.

This paper summarizes some important visual evaluation results done in the past a decade and provides some fundamental ideas how to restore and maintain the Pingyao City wall not only technically correctly, but also in a traditional but more economical way. Further research works are also proposed to monitor the historic city wall, but the quality and durability of implemented maintenance measurements.

2 Options to restore the City Wall of Pingyao

Although many restoration campaigns and daily or weekly maintenance efforts have been done in the past three decades, parts of the city wall are still in danger to collapse (Figure 1). In order to develop an effective but sustainable restoration and maintenance method for Pingyao city wall, in 2006, a research team has been organized under the guidance of the former Chinese Cultural Relics Research Institute (now China Academy for Cultural Heritage), the Bureau of Cultural Relics of Shanxi Province, Pingyao County Cultural Relics Bureau and other organizations. Comprehensive research works have been carried out to systematically analyze conditions[2,3,4] and the causes of deteriorations. The quality of restoration done in the past maintenance practices was also evaluated. One of the targets was to find an optimum receipt and a quality control system to improve the stability of earth for restoration while maintaining the colour and texture of interior finishing.

Figure 1 Internal rammed earth finishing of the Historic Wall of Pingyao (photo taken in 2018). The areas covered by plastic sheets are in danger to collapse.

Laboratory tests show that the loess soil, the main construction material of the Pingyao city wall, is poor in clay[5]. It is not water resistant without any treatment. The stability of earth finishing is affected first of all by erosion on the surface or along cracks (Figure 2) or joints. During rainy seasons, the loess soil can easily be eroded. The second deterioration factor is the leakage through cracks especially along parapet walls and capping pavements. The third factor is the salt damages due to high evaporation.

Figure 2 Erosion of earth and repeated maintenance (photo taken in 2006)

There were three options to restore the interior earthen finishing. First one was to build a masonry with kilned bricks. Second one was to chemically consolidate the soil in situ. The third one was to re-ram a new supporting wall to old earth core, or simplified "earth on earth" option.

Rebuilding with kilned brick masonry would have changed the entire finishing tremendously. It was used previously only as an emergency measure in or shortly before winter season when new rammed earth was not technically applicable. Furthermore, water can still penetrate through the brick joints into earth construction and cause damages, like delamination between brick layer and earth core, which are not so easily detachable.

In situ reinforcement or chemical impregnation would be a possible solution. This technology has been successful in the conservation of non-structural archaeological earthen sites[6,7], but the field experiments in Pingyao inner earth finishing showed that the maximum penetration depth of the impregnation reinforcement agent (ethyl silicate in 99%-concentration) was only 150 mm, which is insufficient to protect the existing rammed earth surface like the eroded earthen finishing shown in Figure 2.

The third option, "earth on earth" option, consists of ramming a new layer of earth construction to protect existing core wall at the same time, to maintain the colour and the texture. Historically, especially during the 1977-1999 period after flooding in 1977, most collapsed walls were restored using this "earth on earth" option. But from 2000, collapses happed even oftener during summer or in the early spring seasons. The main tasks of the research framework in 2006 and 2007 should specify the sustainable methods to consolidate and maintain integrity of the city wall of Pingyao. To do so, it needs first of all to clarify the optimized formula for improving earth and the system of quality control on site.

3 Construction of test areas in 2007

3.1 Type and quantity of lime for loess soil treatment

After comprehensive research works done in 2006[5], it has been found out the loess soil, the main construction material, needs to be consolidated with lime mixture of air lime and hydraulic lime to reach a satisfied level of water and frost resistance. As exposed surface like a building façade, the compacted traditional "three seven lime earth" mixutre, i. e. the mixture is composed of 30wt% air lime, 70wt% loess soil, does not harden properly, and shows less durability. This formulation is also economical because of high dosage of lime. A mixture of two kinds of building limes, quick air lime powder (3-4wt%) and natural hydraulic lime (3-4wt%) has been proven to be more effective to set and harden under the

conventional compaction technique and local workmanship.

The two mock-ups of "earth on earth" option were done in 2007 in the eastern Wall. The first mock up wall was rammed with lime improved earth. The second one was to build supporting wall with adobe plastered subsequently with lime-earth mortars (Figure 3).

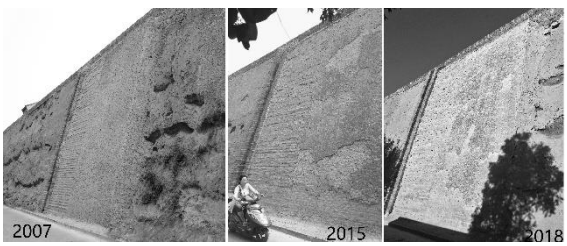

Figure 3 mock-ups finished in 2007 and inspection in 2015 and 2018

The mock-ups were done by the same local workers who had been involved in the daily maintenance works. The mock-ups were so planned to test on the one hand durability of developed formulation and to figure out quality controlling factors, on the other hand whether the developed method is able to be implemented under local workmanship and management system.

3.2 Mock up with rammed earth

The empirical practice showed the old deteriorated soil could not be treated properly to reach required water resistance. Therefore the deteriorated earth was removed to a depth of approx. 800 mm to the core of the city wall. Between the old earth core and new wall, a layer of air lime slurry was applied to minimize the shaking impact to the old earth during the mechanical compaction.

The lime-soil mixture was produced as follows: the fresh soil was excavated from a soil mine app. 15km from the city wall and dried through natural wind and sieved. The sieved soil was premixed dry homogeneously with quick lime powder (3-4wt%) and natural hydraulic lime (3-4wt%) in a warehouse within the ancient city app. 500m away from the mock-up site. The dry mix was transported to the site. On site, app16- 17wt% water was added to the lime earth mixture to get optimum compaction. The lime-soil had been compacted to the highest dry density and subsequently moistured every day during the entire construction period even one week after for proper curing.

3.3 Mock up with adobe and earth plasters

The second mock up wall was built with lime-earth adobe. As a finishing, a 30 mm thick lime earth mortars was applied as "protective" or "sacrificial plaster".

The basement was so prepared as the rammed mock up. The adobe was produced with a conventional brick production line. The earth was mixed with lime as the same formulation for compaction and then extruded and stored for 2 weeks under high humidity within a plastic sheet.

The bedding mortar of adobe wall was composed of 30wt% air lime and 70wt% local soil. Immediately after finished construction of adobe, two layers of protective plasters were applied onto the entire adobe surface. The base plaster was composed of 30wt% air lime and 70wt% soil, same as the bedding mortar, while the top plaster 10wt% air lime and 90wt% soil. The lime-earth mortar was firstly dry-mixed, then water was added to get workable paste and finally the mortar paste was splashed onto the wall with hand. The rough plaster was trowelled to flat before it started to set. The upper layer of lime-earth plaster was impregnated with silicone resin solution (app. 5wt%) one week after completion of plastering with intention to improve the rain water resistance.

4 Visual evaluations of mock ups and completed restoration areas

After 4 years natural weathering, in November 2011, visual inspection and test of strength of rammed lime earth wall have been done to the

rammed earth mock-up. All inspections have given positive results. The colour of rammed earth wall is almost the same as non-treated soil. The maintenance specification as stated in the final report submitted in 2007 by the working group has been confirmed. From July 2012 part of the inner earth wall classified as "dangerous portions" are being restored with the lime （quick air lime and natural hydraulic lime） earth mixture rammed in the traditional way.

The mock up with adobe and lime earth plasters was not evaluated in 2011 because it was not considered as a good option to maintain the entire city wall based on the final report[2].

A renewed visual inspection has been done in Sommer 2018. It has found out that the rammed earth surface was still in good condition, although there was obvious surface deterioration. App. 5-30 mm soil has been eroded based on the height of glass fiber, which was used with intention to lower the surface tension.

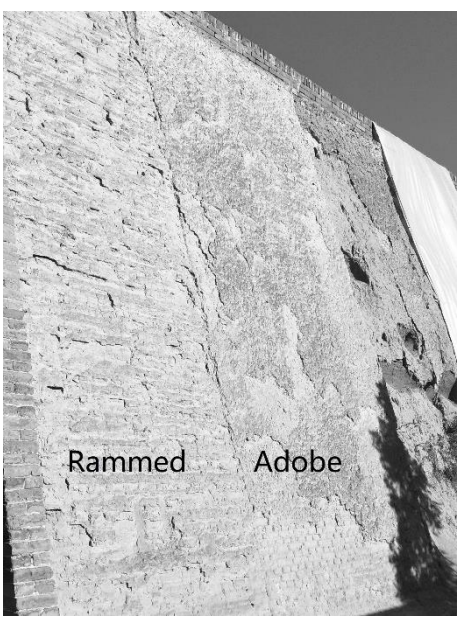

Figure 4 Visual Inspection of mockups near in Sommer 2018

It has also been found the lime-earth plaster to adobe wall in the test area was surprisingly well preserved.

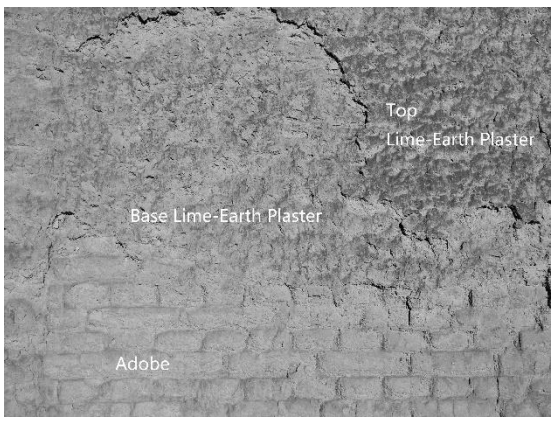

Figure 5 Condition of plastered adobe near most critical area completed in 2007 in details (photo taken in 2018)

There was only app. 20-30% earth plaster has been peeled off after 12 years exposure to natural climate. The delamination occurs both between adobe and base plaster, some delamination has occurred between the base and top plasters. The adobe underneath the lime-earth plaster was relatively well preserved.

The colour of both mock ups are slightly different. The plaster looked darker because more dusts were accumulated on the surface.

The mostly damaged plaster occurred at the top and near foundation. The water repellent impregnation with silicone solution seemed to have not functioned as wished.

5 Conclusions and discussions

It has been concluded that the optimum dosage to stabilize Pingyao loess soil is the mix of quick air lime and natural hydraulic lime. Air lime alone is not effective enough to consolidate the soil with high content of silts to reach the required strength and durability. The total lime content shall be not higher than 10%

to match the colour of not stabilized soil. The optimum dosage in the maintenance practices depends on the clay content of the soil. The higher silt content or the lower the clay content, the higher content of natural hydraulic lime is needed to be mixed to reach sufficient strength and water resistance. High content of water even after compaction guaranties the setting and strength development of lime-soil.

Ramming is an effective method to protect the rammed earth walls while retaining the internal compaction. But the completed areas during 2012-2015 show certain surface deterioration or cracking after a few years' exposure based on visual inspection done in 2015 and 2018 (Figure 6). Those kind of surface defects might not be so extensive to affect the stability of the entire wall, but the causes need to be further studied. From our point of view, a maintenance measurement might be necessary.

The plaster with lime-earth mortars to adobe wall was surprisingly well preserved. The adobe underneath the lime plasters showed less deterioration even 12 years exposed to natural climate.

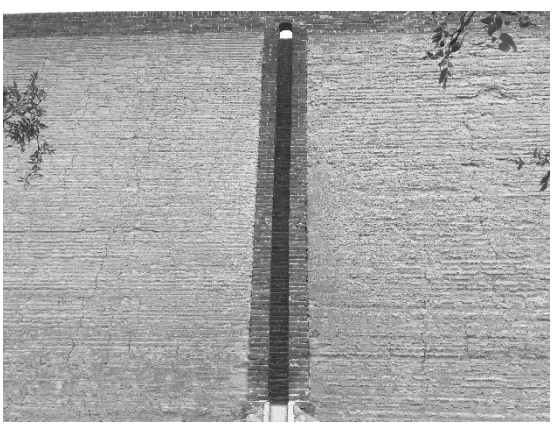

Figure 6 rammed earth with cracks and surface deterioration app 3 years after restoration (photo taken in 2015)

Although to construct adobe wall is economically not reasonable, a protective lime-earth plaster to rammed wall surface could be done both from technical and economical point of view. It could be sustainable solution to maintain the entire wall with very reasonable cost. This lime-earth plaster works as sacrificial layer to regulate the moisture thermal balance and even as a barrier against air borne pollutants, and finally protects the entire surface of the city wall against erosion.

The lime plaster could be applied to the rammed earth wall when cracks and clear surface deterioration occurs. Once the rammed surface deteriorates, there is less appearance difference between rammed finishing and rough lime-earth plaster. Such lime-earth plasters can be repeated every 10 -15 years to avoid most expensive major restoration work.

After submitting the final report by the China Academy for Cultural Heritage in 2007, no further research works have been carried out. The quality-related researches are necessary not only to monitor the historic city wall, but also to understand the quality and durability of implemented maintenance measurements. A small laboratory on site to test some basic parameters, like density, water content, under technical support of a scientific committee is necessary.

The preparation of lime-soil mixture during the mock-ups in 2007 was done in an abandoned warehouse very near the site, but today, all preparation of soil and lime has to be done app 15 km away from the city wall. This distance may influence the quality of compaction since the reaction time of lime-soil mix is limited. Based on the preliminary internal on-going laboratory test results, the reaction time of natural hydraulic lime and formulated wind-slaked lime have high strength after 4-6 hours reaction, while portland cement lime mix has maximum reaction time of 1 hour.

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References

[1]晋中市史志研究院编.平遥古城志[M].北京：中华书局，2002.

[2]中国文化遗产研究院.山西省平遥古城城墙结构加固工程总体设计方案[R].北京：中国文化遗产研究院，2007.

[3] 中冶集团建筑研究总院.平遥古城墙可靠性鉴定报告[R].北京：中冶集团建筑研究总院，2005.

[4] 总装备部工程设计研究总院.山西省平遥古城城墙现状补充调查报告[R].北京：总装备部工程设计研究总院，2006.

[5] Dai Shibing & Li Hongsong, Experimental study on the diagnosis and restoration of the rammed earth surface of the Pingyao City Wall, Heritage Architecture, Vol. 1, 2016-01, 122-129

[6] 王旭东.中国干旱环境下土遗址保护关键技术研究新进展[J].敦煌研究 2008(6):6-12.

[7] 孙满利 王旭东 李最雄.土遗址保护初论[M].科学出版社， 2010