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Causes Analysis and Reinforcement Technology for 21st Horse Wall Cracks of Xi'an Ancient City Wall¹

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Abstract. Xi'an ancient city wall is a national key cultural relics protection units and the most completely preserved ancient city wall building in China. In recent years, the increase of wall cracks has seriously affected the overall performance of the wall, which is in dire need of professional maintenance. Through monitoring the present situation of 21st horse wall cracks, the damage factors and failure mechanism is analyzed in detail. The reinforcement method of steel pipe cast-in-place pile and lime soil compaction pile is proposed based on the existing problems to prevent the expansion of the cracks and maximized preserve the original architecture cultural style, which has reference significance for the protection of ancient building.

1 Introduction

Xi'an ancient city wall is a famous city wall building in ancient China and also the most completely preserved ancient city wall, which has a history of more than 600 years. As an ancient defense installation, it suffers the baptism of war fire. In modern times, during the period of the War of Resistance Against Japan, the War of Liberation, the Cultural Revolution, etc., people dig holes in the walls of the city to take earth and bricks, live, produce, and build civil defense work, which has a great impact on the entire city wall; In the past 30 years, the city wall has served as a city card for Xi'an and a famous tourist and tourism resources, which has received tourists from all over the country and even the whole world. These human activities inevitably make the engineering environment of the city wall more complicated, such as the existence of holes, dense pipelines, the increase of sightseeing facilities and equipment, a large number of people, bicycles, and the increased load of battery traffic, etc., causing deformation and cracks in the city walls. The data show that the cracks in the city wall have become increasingly prominent in recent years, especially the cracks in the horse face are the most serious, accounting for about 90% of the total cracks. The presence of cracks can affect the stability of the wall and even cause the wall to collapse^[1]. This article describes the current situation of the 21st horse wall, and analyzes the formation factors of the crack, the maintenance and reinforcement measures through site survey and data access, which has great



significance to avoid the continuous generation and development of cracks, as well as the later protection of the city wall.

2. Current Situation of 21st Horse Wall Cracks

The 21st horse wall section is located on the east side of the south gate of the city wall (the specific location is shown in figure 1). The surrounding terrain is relatively flat, belonging to the transition zone between the loess tableland and the alluvial plain in the Weihe Basin. The topographic unit belongs to the bench terrace II-2. The main external manifestation of the 21st horse wall's damage is the subsidence and cracks of the city wall's top plane, horse wall and wall of the city wall. The crack measurement, statistics and brief description are shown in Table 1. The specific cracks are shown in Figure 2 and Figure 3.



Figure 1 Traffic Location Map of Xi'an 21st Horse Wall

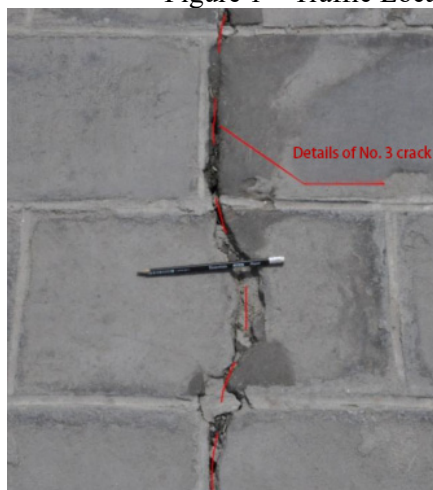


Figure 2 Local Picture of Crack III

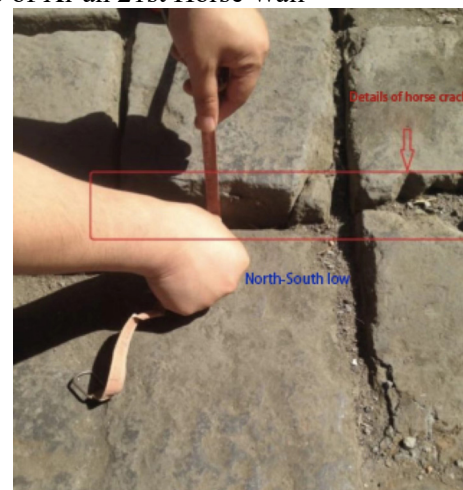


Figure 3 Local Picture of Crack IV

Table 1 Main Cracks of 21st Horse Wall

Crack Location	Mark	Crack state	Crack Size
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city wall's top plane	I	runs east to west, parallel to city wall, lies in the middle of the city wall's top plane	It is about 45m in height and 3~30mm in width.
	II	eastern half moves northward	It is about 13m in height and 3~15mm in width.
	III	runs east to west, the eastern extension of crack I	about 3~25mm in width
horse wall building	IV	southern side of watchtower, runs east to west, the ground tile is high in the south, low in the north	Height difference is 50mm, local crack width is 30mm
	V	Multiple brick walls in the bathroom, extending upwards and northward	
wall of the city wall	F1	The bottom of the wall extends upwards in a vertical direction	Crack width is 10~50mm, narrow at the top and wide at the bottom, the length is about 2/3 of the height of the wall
	F2	The bottom of the wall extends upwards, vertically eastward	Crack width is 10~40mm, narrow at the top and wide at the bottom, the length is about 2/3 of the height of the wall
	F3	The bottom of the city wall extends upwards and penetrates to city wall's top plane	10~40mm in width
	F4 、 F5	The bottom of the wall extends upwards, divided into two cracks at a height of 0.3m of the wall	Crack width is 10~40mm, narrow at the top and wide at the bottom

The investigation also finds that from the height of the city wall's top plane down to the wall within 4m, the weathering and erosion of the city brick is serious, the brick sew was eroded, and the surface of the city brick was denuded and detached, forming a severely uneven wall surface, which is basically distributed in the entire 21st horse wall section, mainly caused by water seepage from top to bottom. The weathering and erosion of the city wall bricks are shown in the photo below.

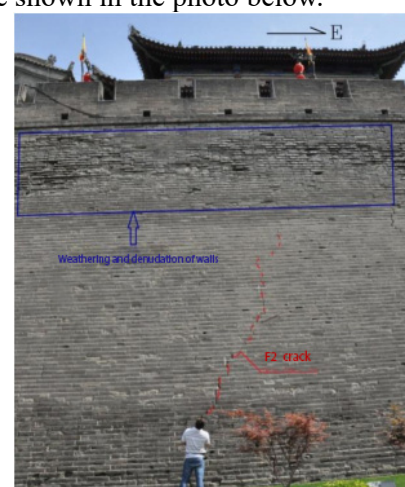


Figure4 F1Weathering and denudation of cracks & walls Figure5 F2Weathering and denudation of cracks & walls

3. Cause Analysis of Cracks

It is concluded that there are the following reasons for the formation of cracks through the wall foundation drilling, literature research, data analysis and surrounding environment investigation of the 21st horse wall section.

3.1 Geological Environmental Effects

Groundwater is exposed by drilling holes in the roots of the horse wall. The groundwater depth is between 7.10 and 8.70m and the corresponding groundwater level is 401.13 to 401.50m, but the measured water elevation of the moat in this area is 401.48m. It follows that the water level of the moat and the groundwater level of the horse wall are approximately the same. The variation trend for the elevation of groundwater level around 21st horse wall in the south gate of Xi'an city wall from 1980 to 2015 is shown in Figure 8. It can be seen from the figure that from the 1980s to the period of investigation (June 2015), the groundwater level of the 21st horse wall has a large variation, and the difference is up to 4-6 m. The reduce of groundwater level will increase the effective self-weight stress in the soil below the original groundwater level, resulting in a large area of additional subsidence of ground surface^[2]; The rise of the water level will increase the compressibility of the soil between the original groundwater level and the changed groundwater level, and for the viscous fill, it will decrease the strength of the soil and increase the earth pressure^[3]. Due to the long-term fluctuation of the groundwater level in which the wall is located, resulting in the uneven subsidence of the foundation^[4], which leads to the occurrence of cracks.

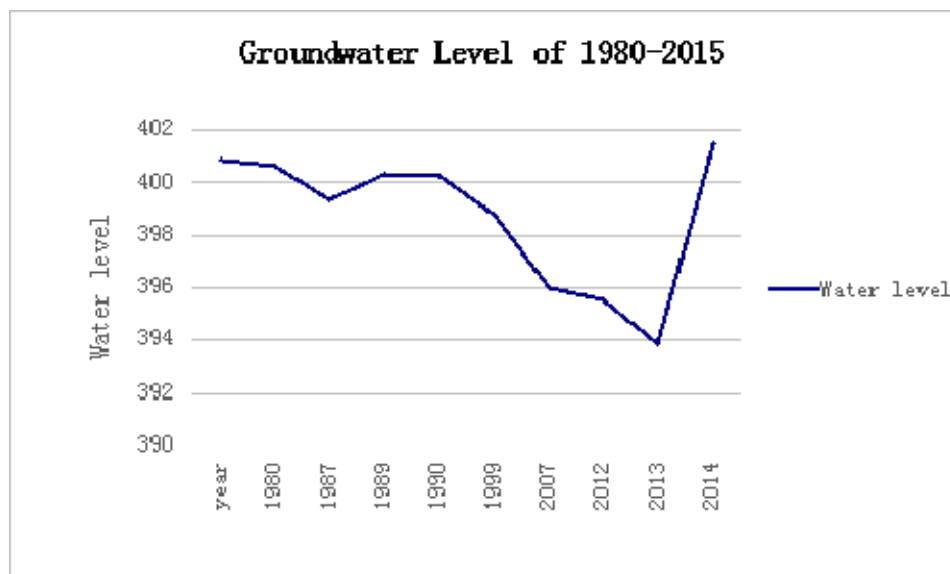


Figure 6 The Variation Trend for the Elevation of Groundwater Level from 1980 to 2015

According to the investigation for the condition of the wall and foundation of 21st horse wall, the city wall is divided into the four layers down from city wall's top plane, including the layer of city bricks①₁, the layer of lime soil cushion①₂, the layer of rammed soil①₃, and the layer of rammed soil ①₄, as shown in Figure 9. According to the statistical table of physical and mechanical properties of each layer, combined with the bearing capacity of each layer of soil, it can be found from situ test that the layer of rammed soil①₃ (about 0.8-7.0m depth) is collapsible loess with poor compactness, poor uniformity and low shear strength; the layer of rammed soil①₅ under the root of the city wall has a large water content, with poor miscellaneous fill, cluttered soil texture, large layer thickness variation and low shear strength; the layer of underlying loess②,③ under the foundation of the city wall are in the state of plastic to plastic-flow, with large water content, medium-to-high compressible soil, and low shear strength. It can be seen that the different soil texture has different moisture content, void ratio, hydraulic coefficient, compression modulus, etc.^[5]. Compared with the overall structure of the

city wall, it is a heterogeneous mass structure with large differences. Concentrated stress points will be formed at the junctions and variable cross-section of different materials^[6]. The occurrence of the cracks in the wall is inevitably under the effect of external load and its deformation.

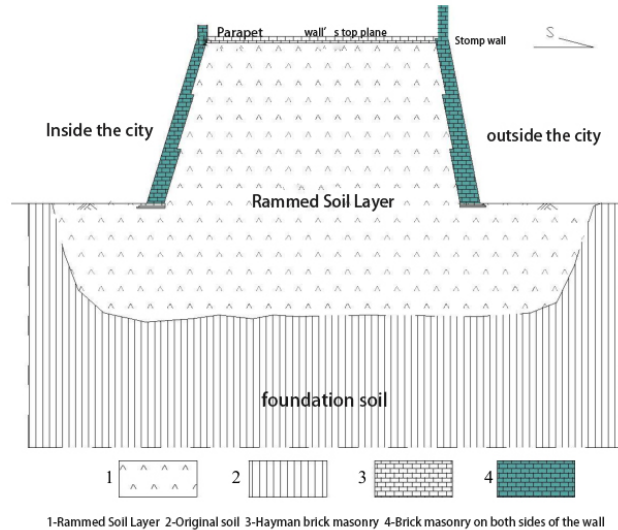


Figure 7 Structure Diagram of City Wall

3.2 Drainage System Effects

According to historical records, it has a complete and standardized drainage system when building the city wall. However, due to the long time, the intact apron structure has not been found here, and only a few of them are completely blocked by silt impurities, and the drainage is unreasonable. Because of the cracks of the city wall's top plane, rain, snow and other objects are immersed in the rammed soil. Due to the different water content between the rammed soil, the soil structure is destroyed after immersion and significant subsidence deformation occurs^[7], resulting in uneven subsidence of the apron structure, and the apron slope fluctuation caused water accumulation, which increased with the development of cracks; the negative topography leads to poor drainage; The possible leakage of the drainage water supply pipeline results in the decrease of the cohesive force and the internal friction angle of the Rammed Soil^[8], the increase of the soil weight results in the increase of the lateral extrusion force of the wall, which is almost equal to the force of compression and shearing resistance of the outside wall, causing the wall to expand and deform. The cracks occur when the pressure reaches its limit stress state.

3.3 Holes and Air-raid Shelter Effects

During the excavation and exploration, many diseases such as holes and air-raid shelters were discovered. As shown in Figure 8, the exploration well t2 is located on the north side of the watchtower. During the excavation process, the air-raid hole is found at a depth of 7.3 m, and no hoop brick is found in the air-raid shelter.

The exploration well t5 is located in the southeast corner of the entire 21st horse wall. During the excavation process, there is a hole at a depth of about 1 meter. There is loose collapsing soil in the hole, the hole is about 0.5m high and extends about 2m to the northwest. See Figure 9 for details.



Figure 8 Air-raid Hole in the Sidewall of Exploration Well t2



Figure 9 Hole in the Sidewall of Exploration Well t5

Xi'an City Wall has experienced the wars of the Ming and Qing Dynasties, and also experienced the War of Resistance Against Japan and the War of Liberation, etc. Especially during the Cultural Revolution, people dig holes in the walls of the city to take earth and bricks and build civil defenses, leaving many holes and air-raid shelters. This has a great influence on the performance of the city wall. According to the pressure diffusion theorem of the ground building foundation, it can be known that the wall deformation and cracks will inevitably occur when the excavation depth exceeds a certain range^[9]. The existence of voids does not provide effective support for the upper building, so that deformation and cracks occur.

3.4 Temperature Variation Effects

Xi'an city is a warm temperate semi-humid monsoon climate zone. The annual maximum temperature is 40°C, the annual minimum temperature is about -12°C, and the maximum temperature difference is 50°C.

Because the bricks and rammed soil of the ancient city wall are poor conductors of temperature, the change of the temperature will cause the thermal expansion and contraction of the material, and the different materials have different shrinkage coefficients with the change of temperature, and the deformation is also different, resulting in inconsistent deformation in the inner part of masonry, masonry and wall, wall, masonry and upper components. When the deformation is restricted by the outside, large shear stress and tensile stress will be generated in the internal component. However, the tensile stress and shear stress of the rammed soil block are relatively small. When the tensile stress and shear stress exceed the ultimate stress state, different degrees of deformation and cracks will occur. The temperature is low in winter, the masonry will freeze and thaw, and when the temperature is high in summer, it will expansion again^[10]. The reciprocating cycle will cause the continuous increase of cracks.

3.5 Human Activities Effects

The 21st horse wall is adjacent to the south gate, which is the key area of tourism development. With a large flow of people, and dynamic loads such as battery cars and frequent tourist activities are concentrated in the south side of the city wall's top plane, while the watchtower is used as a static load on the horse wall for a long time; meanwhile, the both side of 21st horse wall is adjacent to the road, with large the traffic flow, and gathering activities are often held nearby; the frequent construction works inside and outside the city wall, causing vibration on the ground, leading to the increase of the foundation load, etc. These factors will increase the development of cracks.

4. Crack Reinforcement Technology Plan

In summary, the main reason for the occurrence of the cracks in the city wall's top plane is that the rammed soil layer is mostly collapsible loess with poor compactness and poor uniformity, and due to the influence of the change of groundwater level, there is large difference in soil quality of rammed soil layer; secondly, due to the influence of the drainage system, there are cracks in city wall's top plane, and the rainwater is infiltrated into the rammed soil, causing the change of the soil water content, resulting in the decrease of compressibility and the deterioration of shear resistance, which is intensified with the continuous development of the cracks.

4.1 Rammed Soil Layer Encryption

4.1.1 Construction of Steel Pipe Cast-in-place Pile

The pile hole is formed in the foundation soil by the steel pipe compaction, and the steel cage and concrete pouring are placed in to replace the air and moisture in the soil, so that the foundation soil is solidified and compounded into a higher strength soil^[11], which can eliminate the collapsibility of foundation soil and improve the bearing capacity and impermeability of soil^{[12]-[13]}. Moreover, the Steel Pipe Cast-in-place Pile has no noise and no vibration in construction, and has little impact on the surrounding environment. The specific construction method is: leveling the site→mud preparation→embedding guard case→laying working platform→installing the drilling rig and positioning→drilling hole→clearing the hole and checking the quality of the hole→placing the steel cage→pouring the underwater concrete→pulling out guard case→check the quality. The specific arrangements and treatments are as follows:

Construct two rows of steel pipe cast-in-place pile on the south side of 21st horse wall by static pressure. Take the edge of the rammed soil at the bottom of the horse wall as the boundary, and the external expansion of 200mm is the position for the pile core of the first row of steel pipe cast-in-place pile, and the piles is arranged in equilateral triangles. The hole spacing is 400mm, the row spacing is 346mm, altogether 504 piles, the vertical length is 12m, and the actual pile length is shown in the reinforcement section plan. See Figure 12 for details. The Q235B hot-rolled seamless steel pipe is used, the outer diameter is 159mm, the wall thickness is 4.5mm, the end of the pile is placed with a flat-shaped partition, the height of the pile top is -0.500, and the bottom elevation of the stone foundation is ± 0.000 . The steel pipe core is poured with C30 fine stone concrete, the drilling steel is manually vibrated, the slump degree is controlled at about 15cm, and the maximum diameter of aggregate is not more than 25mm. When the concrete in the pile core is poured 600mm away from the top of the pile, the steel cage with the diameter of 120 is inbuilt in the steel pipe pile core and the length of the steel cage into the cap and the anchored steel pipe pile should be greater than 500mm, and the concrete should be poured to the top of the pile. The angle between the two rows of piles from the inside to the outside is 75° and 90° , and the static pressure mechanical construction is adopted. The cast-in-place pile plan is shown in Figure 11.

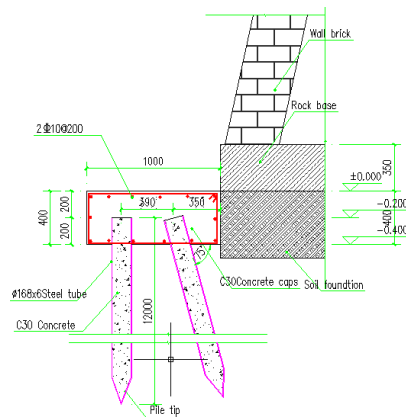


Figure 10 Reinforcement Profile for Steel Pipe Cast-in-place Pile

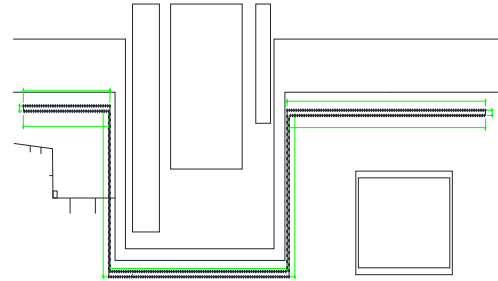


Figure 11 Reinforcement Plan for Steel Pipe Cast-in-place Pile

4.1.2 Construction of Lime Soil Compaction Pile

In view of the collapsible loess, plain fill and miscellaneous soil above the ground water level of the wall foundation, the lime soil compaction pile is used to reinforce the wall according to the existing reinforcement experience^[14]. Drive the steel case into the foundation soil layer with pile driver and then pull it out to form the pile hole, and then fill lime soil into the the pile hole in layers, and then reinforce the foundation through rammed soil. Monitoring should be carried out during the reinforcement process to avoid lateral deformation during the reinforcement process. When the lime soil pile is extruded into a hole, the original soil in the pile hole is laterally extruded, which causes the increase of soil compactness and the decrease of compressibility, so as to to eliminate the collapsibility of the soil^[15]. The specific reinforcement range and process parameters are as follows:

In the length range of east-west direction of the cracks, subsidence, and defects, rammed soil layer ①₃ is reinforced and the thickness of the reinforcement is about 7m below the city wall's top plane. Take the edge of the rammed soil at the bottom of the horse wall as the boundary, drive the lime soil pile to the position at the external expansion of 1100mm, and the pile drilling range is shown in the figure 13. The lime pile is arranged in equilateral triangles. The hole spacing is 500mm, the row spacing is 433mm, altogether 933 piles, the pile diameter is 150mm, the pile length is 12m and the elevation of pile top is -0.500. The actual length of the pile is shown in the reinforcement profile. See figure 12 for details.

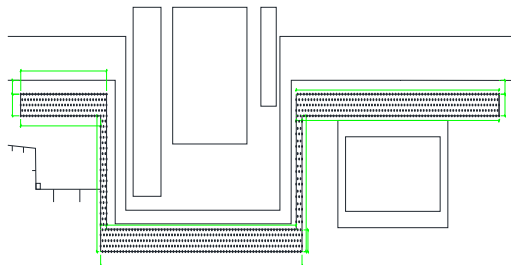


Figure 12 Reinforcement Profile of Lime Soil pile

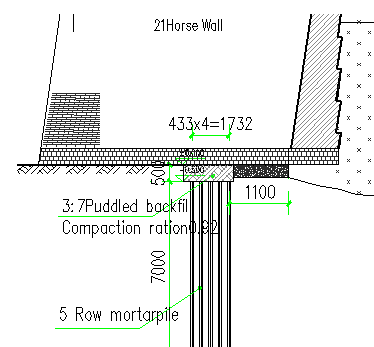


Figure 13 Reinforcement Plan of Lime Soil pile

4.2 Waterproof and Drainage Treatment

A 1m thick 3:7 lime soil cushion should be laid under the city wall's top plane as a water barrier. When the city wall's top plane is built with bricks, it is advisable to design a certain slope to facilitate drainage, so that the rainwater can be quickly drain away. Waterproofing measures should also be

taken to prevent water from entering into the wall foundation from vertical direction, and watering quantity should be controlled in the maintenance of the park lawn around the city; Regular leak detection, overhaul and maintenance for current supply and drainage systems and facilities; The hidden danger caused by unreasonable design should be redesigned and reformed, and multiple waterproofing measures should be adopted in the areas where pipelines are prone to fracture due to complex environment.

During construction, water and rainwater management should be strengthened, and the protection and drainage work for city wall's top plane, horse wall, surrounding walls and floors should be done to prevent water from immersing into the rammed soil and foundation of the city wall. Regardless of the reinforcement measures taken, the feasibility of the construction should be considered and the relevant requirements of the cultural relics system should be met, and the secondary damage to the cultural relics should be minimized.

5. Conclusion

It analyzes the cause of the cracks in the 21st horse wall Xi'an ancient city wall in detail, and take the corresponding measures for the uneven subsidence of the foundation and the shortage of the drainage system. To maintain and reinforce the foundation by steel pipe cast-in-place pile and lime soil compaction pile technology, and take corresponding measures for waterproofing system, which prevents the crack from expanding, improves the structural integrity of the 21st horse wall and achieves the purpose of the protection and maintenance of the ancient city wall. Because different maintenance and reinforcement technologies have their own applicability and limitations, and the importance and particularity of the city wall, the choice of maintenance and reinforcement schemes should be in accordance with specific conditions and make overall consideration on the factors, including historical and artistic value, degree of destruction, use requirement, construction condition and reinforcement cost, etc. to achieve good reinforcement effects.

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