Hygrothermal Evaluation of Waterline Rising of a Masonry Tower based on Measurements and Simulations

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Abstract. Wet walls in ancient masonry buildings are common due to rainfall, groundwater and other environmental factors, and usually accompanied by the degradation phenomena such as powdering, shedding, salting out, which threatens the value and safety of ancient buildings. It is found that the bottom of Dayan Pagoda has been damp and gloomy for a long time. In recent 40 years, the waterline at the bottom has risen by about 0.5 ~1m, and the wet area on the north wall is as high as 5m. This paper aims to clarify the cause of the rising waterline and the water source of Dayan Pagoda. The correlation between degradation of Dayan pagoda and environmental factors such as temperature, rainfall and solar radiation was established. Firstly, there was a field measurement on the waterline height in different orientations of Dayan Tower; Then, a coupled heat and moisture transfer model was developed to obtain the hygrothermal distribution in the brick wall, and the impact of rainfall and groundwater was evaluated, and the rising trend of waterline in the future was predicted. The field measured results show that during 2018-2020, the waterline of the west wall of Dayan Pagoda has the largest rise (about 20cm), while the south wall has the smallest rise (about 10cm). The simulation results show that the water source of rising waterline is mainly wind-driven rain rather than groundwater rising. The result contributes to propose environmental control measures to alleviate the degradation of masonry buildings caused by water.

Keywords. Masonry tower; Waterline rising; Degradation; Hygrothermal simulation.

1. Introduction
Dampness is one of the main reasons for the destruction of historic buildings. Most historical buildings in the world are masonry structures made of porous materials such as bricks, stones, and mortar. The porosity and water absorption coefficient of these materials are relatively large resulting their highly vulnerable to the outdoor natural environmental factors, such as rainfall, solar radiation, salt, and temperature, so that the microstructure of the material changes and loses its own strength, along with degradation phenomenon such as salting out, pulverization, cracking and so on [1-3]. Deterioration not only damage the historical and cultural values of architectural heritage, but also exacerbate the safety risks of the heritage.

Long-term studies have shown that water is one of the main causes of the masonry relics degradation [4-6]. Masonry materials are usually affected by rainfall and groundwater migration to enrich the surface water, which leads to changes in the surface color and hydrolysis of the masonry materials, and also induces freeze-thaw and soluble salt crystallization. Some areas on the surface of the brick wall show a darker color after being eroded by water for a long time, and the "waterline" is the boundary between the wet area and the dry area, which can be clearly identified. Ana S Guimaraes [7] discussed the influence of the wall thickness, material properties and boundary conditions on the height of waterline rising from the ground into the walls of historic buildings under stable state by using the unsaturated water flow theory and numerical verification method. Some research investigated the adverse effect on the masonry materials of wind-driven rain [8-9].
The main cause of various physical, chemical and biological diseases on the historic buildings lies in the transfer and accumulation of heat and moisture in the wall. The difference in the amount and rate of moisture migration leads to the different types and degrees of deterioration. Therefore, it has been widely applied in the protection of architectural heritage to analyze and evaluate the causes of deterioration from the perspective of heat and moisture migration [10-11].

Located in Xi'an, China, Dayan Pagoda is a square seven-tier brick pagoda with a hollow interior. The wall are composed of blue bricks and air-dried earth, with an average thickness of 6m (Figure 1). As the earliest and largest existing brick pagoda of the Tang Dynasty in China, Dayan Pagoda has a long history of more than a thousand years and high value. However, at about 4 meters above the ground, the bottom of the tower has been damp and gloomy for a long time, with pulverization and salting-out, suggesting the intrusion of moisture. As shown in Figure 2, the waterline of the bottom wall in all orientations rose by nearly 1m from the 1980s till now, and the dark area of the north wall even reached 5m high.

![Figure 1. Structure of Dayan Pagoda.](image1)

![Figure 2. Comparison of earlier and current waterlines of Dayan Pagoda.](image2)

Dayan Pagoda, as an outdoor architecture relic, is influenced by the rise of capillary water and the infiltration of precipitation. Xi'an is located in the north China, belonging to the cold and relatively dry region. The average annual rainfall is 544.5mm and concentrated in August, September and October. The groundwater in Xi'an is deep (about 8.60 ~11.80m deep). Therefore, a hypothesis that the rising moisture in the wall mainly comes from the stagnant water in the upper soil after precipitation is put forward.

At present, there is a lack of research on the mechanism of the bottom damp of the ancient brick pagoda. By focusing on Dayan Pagoda, this study follows field investigation and numerical simulation analysis, aiming at investigating the environmental effects on the brick wall deterioration and the moisture source at the bottom, and to analyze the cause of the continuous rising of the waterline.

2. Materials and Methods

2.1. Survey and measurement

The field measurement methods of this study were in-situ observation and photography, collecting and quantifying data. Through field survey and measurement, the waterline rising height in all orientations of the tower during 2018-2020 were recorded, and the results were quantified. The surface wall temperature of the tower was measured by infrared thermal imager in February 2019.

2.2. Heat and moisture transfer simulation

2.2.1. Fundamental equations. Numerical simulation was carried out on the heat and moisture transfer of Dayan Pagoda and the surrounding environment. The model was based on the heat and moisture transfer theory driven by the temperature and water chemical potential, which was proposed by Matsumoto [12]. The finite difference method is used to discretize the basic differential equations, as shown in Equation (1) and (2):
Heat balance:
\[ c \rho \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left[ \left( \lambda + r \lambda' T \right) \frac{\partial T}{\partial x} + r \lambda' \mu g \frac{\partial n_x}{\partial x} - n_x g \right] \]  \hspace{1cm} (1)

Moisture balance:
\[ \rho \frac{\partial \omega}{\partial x} = \frac{\partial}{\partial x} \left[ \left( \lambda' T \mu \right) \frac{\partial \omega}{\partial x} + \lambda' \mu g \frac{\partial n_x}{\partial x} - n_x g \right] \]  \hspace{1cm} (2)

Where, \( c \) is heat capacity (J/kg·K); \( \rho \) is density (kg/m³); \( T \) is temperature (K); \( \mu \) is water chemical potential (J/kg); \( \lambda \) is thermal conductivity (W/(m·K)); \( \lambda' \) is moisture conductivity due to temperature gradient (kg/(m·s·(J/kg))); \( \lambda' T \) is moisture conductivity due to water chemical potential gradient (kg/(m·s·(J/kg))), and \( r \) is phase change heat for vaporization (J/kg), \( \omega \) means liquid water while \( g \) is gaseous phase. \( n_x \) is the direction of water gradient (vertical direction is 1, horizontal direction is 0).

2.2.2. Simulation model of Dayan Pagoda. Simplified from the main section of the brick tower, a two-dimensional hygrothermal simulation model is established and divided into 417*264 grids, as shown in Figure 3. Then a control volume method is adopted for the calculations with a time step of 30 seconds. Boundary conditions of the model include outdoor air temperature, air RH, solar radiation and precipitation. The weather data of the model boundary was the meteorological data for typical year of Xi’an from CSWD (Chinese Standard Weather Data) meteorological database. The moisture conductivity and thermal conductivity of the bricks and soil refer to papers [13-14].

2.2.3. Solar radiation incident on walls with different orientation. Based on the total horizontal solar radiation (\( E_{\text{eo}} \)), the direct solar radiation (\( E_e \)) and diffuse solar radiation (\( E_{\text{SH}} \)) incident on the horizontal surface are calculated by using Equation (3) and (4). Equation (5) and (6) are used to calculate the direct solar radiation of vertical surfaces (\( E_{\text{eV}} \)) and nocturnal radiation (\( E_{\text{eE}} \)).

\[ E_e = E_{\text{eo}} \rho \text{scoth} \]  \hspace{1cm} (3)

\[ E_{\text{SH}} = \frac{1}{2} E_0 \text{sinh} \frac{1 - \rho \text{scoth} - 1.4 \ln P}{1.4 \ln P} \]  \hspace{1cm} (4)

\[ E_{\text{eV}} = E_e \text{cosh} \cdot \cos(\alpha - \alpha_c) \]  \hspace{1cm} (5)

\[ E_{\text{eE}} = \sigma T_d^4 \left( 0.474 - 0.075 \sqrt{T} \right) \]  \hspace{1cm} (6)

Where, \( E_{\text{eo}} \) is the solar constant (W/m²), \( P \) is the atmospheric transmissivity (dimensionless); \( E_{\text{eV}} \) is the direct solar radiation incident on the different vertical surface (W/m²), \( h \) is the sun altitude (°), \( \alpha_c \) is the solar azimuth (°), \( q \) is the inclination angle of the roof (°), and \( \alpha_c \) is the azimuth of the vertical surface (°). \( T_d \) is the absolute air temperature (K), \( f \) is the air water vapor pressure (mmHg).

Figure 3. Simulation model.  \hspace{1cm} Figure 4. The relationship between water content and RH of brick.

2.2.4. Determination of maximum height of waterline rise. The RH of the brick surface is given by the equilibrium relationship of the brick material properties. The characteristics of equilibrium moisture content of traditional Chinese blue bricks were used to determine the maximum height of waterline (Figure 4). It can be seen from the curve that when the moisture content of the brick surface is greater than 0.02, the relative humidity is greater than 99%. Therefore, the height at which the surface moisture content lower than 0.02 is considered as the maximum height of waterline rise in this research.
3. Results

3.1. Survey and measurement results

3.1.1. Rising characteristics of waterline on walls with different orientations. Figure 5 is the photos of the moist areas in different orientations walls in 2018 and it can be seen that the waterlines reached different heights. Overall, the waterline in the north was the highest (5m), and the waterline in the south was the lowest (4m). The area accessible to capillary water in the south is about 1m lower than the north maybe caused by the strong radiation and the resulting high temperature, and high evaporation in the south. The lower waterline at the doorway indicates capillary water rise rather than rainwater infiltration, because the rainwater would cause the waterline of the entire wall to be at the same level. It was observed that there were more diseases in wet areas than in dry areas. The north wall has a larger wet area, higher waterline, and more serious diseases such as salting-out and pulverization.

Figure 5. Waterline heights in different orientations in 2018.

Figure 6 shows the record of waterline rising in 2018-2020. Between 2018-2020, the waterline in each orientation has a slight rise. The waterline tends to be slightly lower at the corners and openings of the brick walls in each orientation, and higher in the middle. The north wall waterline has the highest average height of 5m.

| Date         | SOUTH | EAST | NORTH | WEST |
|--------------|-------|------|-------|------|
| 2018.08.19   | ![Image](image1) | ![Image](image2) | ![Image](image3) | ![Image](image4) |
| 2019.03.10   | ![Image](image5) | ![Image](image6) | ![Image](image7) | ![Image](image8) |
| 2019.08.09   | ![Image](image9) | ![Image](image10) | ![Image](image11) | ![Image](image12) |
| 2019.10.04   | ![Image](image13) | ![Image](image14) | ![Image](image15) | ![Image](image16) |
| 2019.12.15   | ![Image](image17) | ![Image](image18) | ![Image](image19) | ![Image](image20) |
| 2020.06.13   | ![Image](image21) | ![Image](image22) | ![Image](image23) | ![Image](image24) |
| 2020.09.04   | ![Image](image25) | ![Image](image26) | ![Image](image27) | ![Image](image28) |

Figure 6. Record of waterline rising in 2018-2020.

The waterline has risen by 8~15cm (1-2 brick height) on average, and 20~30cm (3-4 brick height) in some areas (Figure 7(a)). During these two years, the west and east wall had the largest waterline rise (about 20cm) and the south wall the smallest (about 10cm). It is speculated that this is mainly due to the wind-driven rain
mainly comes from the west and east, which makes the wall of the west and east to absorb and store more rainwater, causing the waterline to rise more. While in the south, where there is more solar radiation and evaporation, water is harder to store so that waterline rises the least. As shown in Figure 7(b), the main rising uptrend is in 2018-2019, while the 2019’s and 2020’s waterlines almost coincide with each other, only with darker color. The survey results show that the formation of waterline goes through the repeated infiltration process of dry season and rainy season, which is not a direct continuous rise, but after many times of deepening, weakening and spreading process, the dark parts on the wall surface are formed.

3.1.2. Influence of seasonal precipitation. The two-year survey also showed that the brick walls were contaminated by seasonal wall surface runoff, with traces of water flowing down from the eaves of the tower in June and disappearing in August (Figure 8). Vertical waterline appeared or disappeared with the alternation of rainy and drought seasons, but the light color mark remained after the disappearance. It is speculated that the disappearance of the marks of wall surface runoff is due to the strong solar radiation and evaporation in August.

3.1.3. Measured results of wall surface temperature. As Figure 9 shows, the wall temperature of the dark wet area is 1~3℃ higher than that of the upper part, mainly because of the larger heat absorptivity, indicating that the surface water content of the dark area at the lower part may be lower than the upper. It is speculated that the black area is the irreversible color change of the brick surface caused by the growth of microorganisms by the chemical contamination in rainwater.

3.2. Heat and moisture transfer simulation results

3.2.1. Comparison of wall temperature in different orientations. Figure 10 shows the simulated results of hourly wall surface temperature of the south and north wall. It can be seen that the wall temperature of the south is obviously higher than that of the north, and the large temperature difference between the north and the south is mainly due to the large difference in solar radiation. The surface temperature of the north wall fluctuates less than that of the south wall throughout the year, and there are fewer days when the temperature exceeds 40℃ in the north. Also, we can see that in the same orientation, the higher point has the higher maximum daily temperature and the greater wall temperature fluctuation.
3.2.2. Comparison of water content in different orientations. Figure 11 shows the comparison of surface moisture content in different orientations at different heights, which is also the case that only the influence of shallow groundwater and no rain falls directly on the vertical wall is considered (Case 1). The moisture content of north wall is higher than the south wall at the same height, which is coincidence with the Figure 5 that the waterline of the north wall is higher than the south wall. When no rain falls directly on the wall, the surface moisture content of the south and north walls above 0.8m height is very low. On rainfall days, water content shows a sudden rise and close to saturation. The moisture content in the middle and lower part fluctuates greatly, which is consistent with the serious wall deterioration at around 0.5m high in the filed survey.

![Figure 10. Surface Temperature at different heights of South and North](image1)

![Figure 11. Relationship between water content and Rain](image2)

4. Discussion

In follow, the maximum height of waterline rising and its causes will be discussed by numerical simulation that consider different environmental factors.

4.1. Correlation between wall temperature and waterline height with different orientations

Figure 12 shows the comparison of hourly wall temperature of different orientations. It can be seen from Figure 12(a) that the wall temperature of different orientations is basically consistent with its total solar radiation value. The temperature of the west wall is the highest and the high temperature is concentrated in summer, even reaching more than 50°C, which is mainly because the solar radiation in the west is larger in summer. In winter, the solar radiation on the south was highest, which resulted in highest temperature on the south wall and the largest fluctuation. The temperature fluctuation of the north wall is smallest throughout the year, and the temperature is below 0 °C, in winter, which is prone to freeze-thaw.

![Figure 12. Correlation between wall temperature and waterline height](image3)

(a) Hourly temperature of different orientations  (b) Waterline height of different orientations

As can be seen, the north and the east with lower wall temperature and less temperature fluctuation, have the higher waterline; The south and west with higher temperature and larger temperature amplitude throughout the year have lower waterline. Therefore, it is speculated that the waterline height is related to the temperature fluctuation and the evaporation in different orientations.
4.2. The maximum height of waterline rising

Here, we considered three cases that one is the rainfall does not fall directly on the vertical wall, but only on the horizontal surface (Case 1), and one is that a certain amount of rainfall hits the vertical wall directly and is absorbed by brick (Case 2), and one is that the wind-driven rain hits the wall directly (Case 3). In case 2, the rainfall on the vertical wall is one-third of the total rainfall, while in case 3 it depends on wind speed and direction.

Figure 13 shows the simulated maximum waterline height of three cases. In case 1, the maximum waterline height at different orientations is 1.2 m that is much lower than the measured value. However, the waterline height in Case 2 can reach more than 3m, much closer to the measured value. Considering the wind-driven rain (Case 3), since the east and the north wind were dominant and received more rainfall, the simulated waterline height in the east and north increased correspondingly, which was closer to the measured waterline height.

Therefore, the moist area on the bottom wall is not only due to the effect of capillary water rise, but is more related to the wall’s direct absorption of rainfall (WDR).

![Figure 13. Comparison of simulated and measured waterline height](image)

![Figure 14. The relationship between waterline rise and precipitation](image)

4.3. Correlation analysis of waterline rise and precipitation

Figure 14 is the diagram of the relationship between waterline rise and precipitation. Due to the slight slope of the wall, the rain falling from the edge of the eaves falls on the middle part of the wall, where the brick wall is most severely damaged and is the first to suffer from breakage, salting out, and pulverization (large white area of salting out can be seen), and the bricks there were the first to be replaced. Rainwater absorbed by the bricks in the middle of the wall infiltrates in all directions, with the upward water extending the dark area and known as waterline rise. The lower waterline around the hole (entrance) is probably due to the fact that the water falls almost directly there and cannot be absorbed and stored by the brick, so less water infiltrates up, and the waterline is lower than the sides. The dark wet area of the tower is mainly from precipitation.

Also, rain permeates into the ground, forming the upper stagnant water, rising along the brick wall, carrying salt components as the brick dries and crystallizes, resulting in large salting out, powder and other deterioration formed about 1m from the ground.

4.4. Analysis and prediction of precipitation change and waterline rise

Figure 15 shows the total precipitation in Xi’an from 1951 to 2020, ranging from 312.2mm (1995) to 903.2mm (1983). The total rainfall in more than half of the years was greater than the typical year precipitation used in the model. Figure 16 shows the moisture content of the north wall at the height of 0m and 5m in the years with less rain, more rain and typical meteorological years. The results show that the moisture content of the same height is the highest in the rainy year, followed by the typical year, while the less rainy year is the lowest. This is mainly due to the different effects of rainfall on water content in the years with different precipitation. When there is more rain, the vertical wall receives more rain directly and absorbs more water.

It can be seen that the annual total precipitation has a great influence on the wall moisture content of the tower. Therefore, according to the precipitation, the rising trend of the wall waterline could be predicted in the future. If the precipitation increases year by year, the waterline of the tower is likely to continue to rise. If the annual precipitation were about the same, the waterline would probably remain the same, but since the current
dark area is an irreversible color change on the brick surface caused by various factors such as microbial growth, the waterline will not decrease even if the rainfall decreases.

Figure 15. Annual total precipitation in Xi’an during 1951-2020

Figure 16. Comparison of water content of the north wall under different precipitation

5. Conclusion
The objective of this study was to investigate the quantitative relationship between waterline rising of brick tower and the environmental conditions. According to the results, the following conclusions are drawn.
(1) Wet areas and waterline height differs in different orientations, mainly due to the different wall temperature caused by different solar radiation and the different moisture content caused by the different amount of rainwater absorption. The south side has the greatest amount of solar radiation, more evaporation, and the lowest waterline; while the north and east wall receive more rainfall and have the lowest temperature and highest water content, presenting the larger wet area and higher waterline, and the more serious brick wall degradation.
(2) The measured results show that between 2018-2020, the waterline of Dayan Pagoda in each direction has a slight rise. The waterline of the west and east wall has the largest rise (about 20cm), while the south wall has the smallest rise (about 10cm), and this is consistent with the dominant WDR direction being east and west.
(3) The simulation results show that the dark areas on the brick walls are mainly caused by the direct absorption of rainfall. The increase in the total annual rainfall will cause the continuous rise of the waterline of the bottom wall, and the waterline in the dominant direction of wind-driven rain tends to rise more.

Acknowledgments: This work was supported by the National Nature Science Foundation of China [grant number 51878140], and the China National Key R&D Program during the 13th Five-year Plan Period [grant numbers 2019YFC1520901].

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