Role of urban plant environment for sustainable protection of an ancient city wall

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Abstract

Cultural heritage sites are exposed to urban environmental phenomena and various forms of deterioration that degrade their historical and cultural value. As an important element, plants landscaping can be a potential regulator of the micro-environment mitigating the adverse effect of the local climate to cultural heritage. The influence of evergreen trees on the weathering deterioration of Nanjing City Wall was studied and evaluated through field measurements and numerical modelling. A two-dimensional hygrothermal ‘City Wall–plant’ model was developed to simulate the shaded and unshaded surfaces. The results showed that compared with the unshaded case, the shaded surface showed smaller temperature fluctuations with an increase in the minimum temperature by 0.5 ~ 0.8°C, smaller water content fluctuations with a decrease in the standard deviation by 0 ~ 0.04 m³/m³, and a lower evaporation rate by 8~18%. This means that the evergreen trees can effectively reduce the risk of deterioration on wall surfaces due to freeze–thaw cycles, efflorescence, and subflorescence. These findings provide with the theoretical basis for the sustainable preservation of sites with cultural heritage.

Keywords: Heritage conservation; Plant regulation; Hygrothermal simulation; Risk of deterioration; City wall;

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1 Introduction

Cultural heritage is a witness of cultural values, shared by people during a period. Heritage must be preserved in order to be passed down to the future generations [1]. However, cultural heritage such as buildings, structures and archaeological sites, are directly exposed to the natural environment, and are often affected by solar radiation, precipitation, underlying surface and other climate factors [2, 3], facing weathering, man-made destruction, natural disasters and other threats.

The microclimate fluctuations at sites of architectural heritage can seriously affect the rate of buildings' degradation and deterioration. The large-scale brick City Wall (Nanjing, China) is a monument of great heritage exposed to the natural environment, which due to the physical properties (high porosity, high water absorption, etc.) of the brick, it is easier to be deteriorated. Jin and Zhang et.al found that phenomena of efflorescence, exfoliation, pelletizing, powdering, and flaking on wall bricks, are often related to the rise of salt-containing capillary water, as well as in differences in the concentration and type of the ions therein [4, 5]. Waragai et.al found that the base of sandstone pillars in Angkor Wat temple, having different orientations, were deteriorated to diverse degrees; this was mainly attributed to direct exposure to solar radiation together with rainfall [6]. Erkal et.al also proved that the erosion and degrading strength of building materials is effected by the wind-driven rain [7]. Moreover, D'Ayala et.al investigated the adverse effect of the rain under extreme climate conditions on the preservation of historical buildings [8]. Consecutive freeze-thaw cycles may also lead to the reduction in structural/mechanical strength of porous building materials [9], i.e. stone and bricks, another key factor of architectural heritage deterioration. The degree of the freeze-thaw damage is directly related to the frost temperature and moisture content [10]. Accordingly, Zhou et.al further investigated the influence of climate change on freeze-thaw risk of internally insulated masonry walls [11].

Typically, an appropriate, well regulated hygrothermal microclimate will benefit the architectural heritage conservation. Studies have shown that vegetation has the capacity to regulate the microclimate in urban environments. Specifically, trees with giant canopy are able to

reduce downward short-wave radiation [19], decelerate the wind speed, cool down the surrounding area through respiration [20], regulate the ambient air temperature and humidity [21, 22]. Employment of plantation(s) to mitigate the adverse environmental impact of phenomena to building elements is a very common strategy, 'green' roofs and/or 'green' walls often built to decrease the surface temperature and regulate the internal buildings' environment [23, 24]. Researches trialled different species of trees and showed that their effect on environmental regulation varies per speciation [25]. Fundamental species-based features are, tree arrangement, amount of leaves, Leaf Area Index and other tree crown-related characteristics [26, 27]. Furthermore, the potential of vegetation in regulating microclimate has been explored in heritage protection applications. It is well known that vegetation near the archaeological site reduces the risk of thermal shocks and makes the relative humidity optimal for buildings' preservation [28]. For example, English ivy has been found to reduce the range and variability of wall-surface microclimates over diurnal, seasonal, and annual timescales [29] as well as to reduce the frequency, duration, and severity of freezing events [30] at historic sites in England. Another study showed that presence of vegetation in close proximity to an ancient temple regulates its ambient environment significantly minimizing the stone loss effect [31]. These findings shout of the beneficial character of plantation in the conservation of buildings' heritage. Essentially, the shading of trees may offer a potential solution for the preservation of largescale heritage sites. However, regulation of heat and humidity phenomena at heritage sites, by introducing plants, is a mechanism that remains unexplored. We hypothesize that their presence may promote preservation; however, the mechanism and the exact impact of plantation to the conservation of cultural heritage via tackling weathering and degradation is yet unclear.

Nanjing City Wall (N: 32°06"; E: 118°79"), one of the most important cultural heritages in China, has a long history that can be traced back over 600 years. It is an ancient structure of enormous historical and cultural heritage value, among which are inscriptions that contain information of responsible organizations and persons on the bricks [33]. However, Nanjing City Wall has been exposed

to climatic variations for centuries and deteriorated by peeling and cracking which damaged surface inscriptions.

This study aims to evaluate the influence of trees around the wall on the weathering deterioration of the Nanjing City Wall was studied and evaluated through field measurements and numerical modelling. The results were used to formulate guidelines for the landscape design around the City Wall, hoping to further promote the rationalization behind sustainable development and management of urban landscape design.

2 Materials and methods

A field parameters' measurement and simulation approach was adopted for this research work. Specifically: field measurements, the influence of trees on the hygrothermal characteristics of the wall surface were preliminarily evaluated. Then, due to limited measurement conditions, simulation was used for the evaluation of the influence of trees on the risks from freeze-thaw and salt crystallization to a masonry wall, the Nanjing City Wall in this study.

2.1 Measurements

Nanjing city is located at Eastern China, subjected to the Yangtze River. In year 2019, the temperature fluctuated between -2.6°C and 40°C with average temperature of 17°C ; the relative humidity fluctuated between 15.8% and 100%. The annual average rainfall was 1245 mm for the last 10 years. Jiefang gate is one of the gates located at the northern part of Nanjing City Wall. Two parts (Site 1 and Site 2) were selected and measured on the west of Jiefang gate from April 2019 (Fig. 1a). There was a 7.5m high Osmanthus tree (evergreen) about 3.5m away from the south facade of City Wall at Site 1. The air temperature and relative humidity under the canopy, the surface temperatures and water content of the City Wall were measured. The temperatures were measured at heights of 1.2 m, 3.9 m, and 5.4 m, and the water content were measured at heights of 0.15 m, 1.2m, and 2.1 m (Fig. 1b). Hereafter, these heights are denoted as $H_{0.15}$, $H_{1.2}$, etc.

Site 2 was selected about 14 meters apart from Site 1. On the south side of Site 2, there is a 5 m-high Osmanthus tree about 5 m away from the City Wall. The tree shades the lower part of the wall surface only for a limited period of the year. The

temperature was measured at a height of 3.9m ($H_{3.9}$) from the ground to represent the temperature on an unshaded surface (Fig. 1c). This point is hereafter regarded as the unshaded point.

The surface temperatures at three heights ($H_{1.2}$, $H_{3.9}$, and $H_{5.4}$), and ground surface temperature were measured by T-type thermocouples and recorder (type: GRAPHTEC GL240; origin: Japan; precision: $\pm 0.5^{\circ}\text{C}$; measurement range: $-200^{\circ}\text{C} \sim 400^{\circ}\text{C}$) powered by a solar panel. The air temperature and humidity under the canopy were measured by electronic temperature and humidity recorders (type: HOBO MX2301; origin: America; precision: $\pm 0.2^{\circ}\text{C}$ and $\pm 2.5\%$, respectively; measurement range: $-40^{\circ}\text{C} \sim 70^{\circ}\text{C}$ and $0\% \sim 100\%$, respectively).

The water content was measured by a moisture meter (type: Testo 616; origin: German; precision: $\pm 0.1\%$; measurement range: $0\% \sim 20\%$). The water content of the brick over a depth of 5 cm was measured by this sensor. The 10 horizontally consecutive bricks were measured at three heights ($H_{0.15}$, $H_{1.2}$, and $H_{2.1}$). The average value of 10 bricks was used to represent the water content at each height.

The air temperature and relative humidity under the canopy, and surface temperatures were recorded every 30 minutes from June to December in 2019, and the water content measurements were conducted on every ten days from April to December in 2019.

The meteorological data were recorded by HOBO Station (type: HOBO RX3003; origin: America) located at Southeast University (800 m apart from the monitored site). The monitored weather data included the temperature, relative humidity, rainfall, and horizontal global solar radiation, which were recorded at 5 minutes' intervals. The measurement range of the air temperature, relative humidity, rainfall and solar radiation are $-40 \sim +75^{\circ}\text{C}$ (precision: $\pm 0.21^{\circ}\text{C}$), $0 \sim 100\%$ (precision: $\pm 2.5\%$), $0 \sim 12.7\text{cm/h}$ (precision: $\pm 1\%$), $0 \sim 1280\text{W/m}^2$ (precision: $\pm 10\text{W/m}^2$), respectively.

(a)

(b)

(c)

Fig. 1 Environment monitoring: (a) Photos of monitoring sites; (b) Measure points at Site 1; (c) Measure points at Site 2

2.2 Simulation model

2.2.1 City Wall-Plant model

A City Wall-Plant model proposed for this research, presented schematically in Fig. 2. The model contains four elements: the ground, city wall, canopy, and the air space under the canopy. They are all assumed porous materials. The calculation of the energy and water budget quantifies both the flow of heat and moisture that occur in the ground, from

the city wall, the canopy, and the air space under the canopy.

Based on the meteorological data, the exchange of heat and moisture at all interfaces (ground/city wall–outdoor air, canopy– outdoor air, and ground/city wall–the air under the canopy) were calculated.

In the plant model, the canopy can reduce the incident solar radiation to the shaded ground and wall surface, and intercept the rainfall that dropped to vertical projection region (the ground and wall).

As a result, the temperature and moisture content of these elements were decided. These parameters interact with each other, thus, they were calculated by solving them simultaneously. Based on the obtained simulated results (temperature and moisture content of the wall surface) we could evaluate the deterioration of the wall, and subsequently the effect of the plant to the wall status.

2.2.2 City Wall model

Araoka et al. built a two-dimensional hygrothermal model of Nanjing City Wall, which considered a composite structure consisting of brick and mortar, to examine the influence of rainwater infiltration [32]. As we focused on the influence of vegetation on the hygrothermal state of City Wall, it was simply modeled as a full brick structure. The simultaneous transfer model of heat and water by Matsumoto [34] was adopted in this paper. In this model, the water chemical potential μ is used to express the moisture state. The relationship between μ , temperature, and relative humidity is given as follows:

$$\mu = R_v T \ln(h) \quad (1)$$

Heat balance equation:

$$c\rho \cdot \frac{\partial T}{\partial t} = \nabla[(\lambda + \lambda'_{Tg})\nabla T + r\lambda'_{Tg} \nabla \mu] \quad (2)$$

Moisture balance equation:

$$\rho_w \left(\frac{\partial \Psi}{\partial \mu} \right) \left(\frac{\partial \mu}{\partial t} \right) = \nabla[\lambda'_\mu (\nabla \mu - g\mathbf{n}) + \lambda'_T \nabla T] \quad (3)$$

2.2.3 Plant model

Plant models have been extensively studied. Frankenstein et al. [35] proposed low-vegetation (shrubs, crops, grass, etc.) and high-vegetation models (trees and canopy) based on a previous model [36–38]. Low-vegetation models have been studied and applied to analyze the thermal behavior of the green building envelope or the building's energy consumption [39, 40].

In our model, trees played the role of reducing solar radiation to and the nocturnal radiation from the wall. Furthermore, the rainwater trapped by trees evaporates and removes heat from the plants. The model was based on the plant model by Kondou [41], and was applied to the shaded ground and walls. The plant model was developed consisting of two nodes: one representing a homogeneous canopy of trees and the another for the air space under the canopy. Fig. 2a-2b shows the thermal and moisture networks of the developed plant model, in which, the thermal resistance, the transmittance coefficient of the canopy to solar radiation and rain were used to characterize the canopy structure of trees. The equations of heat and moisture balance of the plants are shown on Appendix B.

266 2.3 Calculation method

An explicit control volume method was adopted for the calculations with a time step of 30 seconds. The initial conditions of the calculation were determined by the relevant annual cycle data, carried out in City Wall-Plant model using the weather data monitored by the year 2018 (repeatedly for 10 years). Fig. 2c shows the region of calculations and the boundary conditions. The two-dimensional calculation region ($44.5\text{m} \times 34.8\text{m}$) is divided into $451(\text{horizontal}) \times 176(\text{vertical})$ meshes with different mesh size. A third kind of boundary conditions was used at the ground-air and wall-air boundary surfaces. At the bottom of the calculation region (-15m under the ground surface), the boundary conditions refer to the first kind of boundary conditions (temperature is 17°C and water chemical potential is -5 J/kg).

The heat and moisture flux on the boundary of the of the unshaded wall/ground surface (Boundary A in Fig. 2c) is expressed as follows:

287 Heat:

$$\begin{aligned}
& (\alpha_{om} + r\alpha'_T)(T_o - T_m) + r\alpha'_\mu(\mu_o - \mu_m) + I_{sol} \cdot A_m - \epsilon_m \cdot I_{noc} \\
& = -(\lambda + r\lambda'_{Tg}) \frac{\partial T}{\partial n} \Big|_s - r\lambda'_{\mu g} \frac{\partial \mu}{\partial n} \Big|_s \quad (4)
\end{aligned}$$

290 Moisture: $P_r + \alpha'_\mu(\mu_o - \mu_m) + \alpha'_T(T_o - T_m)$

$$291 \quad = -\lambda'_\mu \cdot \left(\frac{\partial \mu}{\partial n} \right)_s - n_x \cdot g \Big) - \lambda'_T \frac{\partial T}{\partial n} \Big|_s \quad (5)$$

The heat and moisture flux on Boundary B in Fig. 2c is expressed as follows:

294 Heat:

$$\begin{aligned}
& (\alpha_{om} + r\alpha'_T)(T_o - T_m) + r\alpha'_\mu(\mu_o - \mu_m) + \gamma \cdot (I_{sol} \cdot A_m - \varepsilon_m \cdot I_{noc}) \\
& = -(\lambda + r\lambda'_{Tg}) \frac{\partial T}{\partial n} \Big|_\varsigma - r\lambda'_{\mu g} \frac{\partial \mu}{\partial n} \Big|_\varsigma \quad (6)
\end{aligned}$$

$$\text{Moisture: } \gamma' \cdot P_r + \alpha'_\mu (\mu_o - \mu_m) + \alpha'_T (T_o - T_m) \\ = -\lambda'_\mu \cdot \left(\frac{\partial \mu}{\partial n} \right)_s - n_x \cdot g - \lambda'_T \cdot \left. \frac{\partial T}{\partial n} \right|_s \quad (7)$$

The temperature and relative humidity of the air under canopy were calculated by Eq. (B5), (B7), shown in Appendix B, for the calculation needs, one particle indicates the air under canopy. The heat and moisture flux on Boundary C in Fig. 2c is expressed as follows:

Heat:

$$\begin{aligned} & (\alpha_{am} + r\alpha_T)(T_{as} - T_m) + r\alpha'_\mu(\mu_{as} - \mu_m) + \gamma(I_{sol} \cdot A_m - \varepsilon_m \cdot I_{noc}) \\ & = -(\lambda + r\lambda'_{Tg}) \left. \frac{\partial T}{\partial n} \right|_s - r\lambda'_{\mu g} \left. \frac{\partial \mu}{\partial n} \right|_s \quad (8) \end{aligned}$$

Moisture: $\gamma' \cdot P_r + \alpha'_\mu (\mu_{as} - \mu_m) + \alpha'_T (T_{as} - T_m)$

$$= -\lambda'_\mu \cdot \left(\frac{\partial \mu}{\partial n} \Big|_s - n_x \cdot g \right) - \lambda'_T \frac{\partial T}{\partial n} \Big|_s \quad (9)$$

(c) The illustration of the calculation region and the boundary conditions

Fig. 2 Schematic diagram of heat and moisture transfer in plant model: (a) thermal nodal network; (b) moisture nodal network.; (c) the illustration of the calculation region and the boundary conditions.

3 Measured and Calculated Results

3.1 Measured results

3.1.1 Air temperature and relative humidity under the canopy

Fig. 3 shows the measured air temperature and relative humidity under the canopy at Site 1 along with the meteorological (outdoor) data. During the monitoring period (Jun. 2019 - Dec. 2019), the temperature fluctuation range of the air under the tree and outdoor air were 35.9 °C (1.8 °C ~37.7 °C), and 38.4 °C (1.6 °C~40 °C), respectively. In summer, the air temperature under the canopy was lower than the outdoor air throughout the day, with a maximum temperature difference of 6.1 °C. In addition, the relative humidity under the canopy was higher than the outdoor air for most of the time. The relative humidity difference was between 27%~8%.

3.1.2 Surface temperature and water content of City Wall

Fig. 4a shows the measured surface temperatures at shaded $H_{1.2}$, $H_{3.9}$, $H_{5.4}$ and ground surface at Site 1 and the unshaded $H_{3.9}$ at Site 2. Part of the temperature data was missing when the temperature

recorder equipment was not powered. In summer, almost small differences between the daily minimum temperatures and large differences between the maximum values were seen on measured points, while the temperature differences decreased in winter. In addition, due to the low solar altitude in winter, the measurement point at Site 2 was partly shaded by trees, and the temperature fluctuation was similar with those at the shaded points.

Fig. 4b shows the average water content of 10 horizontally consecutive bricks at three heights ($H_{0.15}$, $H_{1.2}$, and $H_{2.1}$) at Site 1. The water content at the shaded surface decreased with height and showed a similar fluctuation trend at the three heights. During the monitoring period, the water content was obviously affected by rainfall. The water content was higher in rainy season (July and August), while lower in arid season (September and October).

Fig. 3 Temperature and relative humidity under the canopy and at meteorological station (Jun. 2019 - Dec. 2019)

(a)

Fig. 4 Measured surface temperatures and water content at Sites: (a) Measured surface temperatures at three heights ($H_{1.2}$, $H_{3.9}$, and $H_{5.4}$) and ground surface at Site 1, and unshaded $H_{3.9}$ at Site 2; (b) Average water content at heights ($H_{0.15}$, $H_{1.2}$, and $H_{2.1}$) at Site 1.

3.2 Validation of proposed model

A two-dimensional ‘City Wall–plant’ model was set up by FORTRAN language to simulate the shaded wall at Site 1 (Fig. 1a). Different interception coefficients were used to represent the canopy characteristics in the unshaded and shaded cases. For a shaded case, the tree is evergreen with a height of 7.5 m, a canopy diameter of 7 m, a distance of 3.5 m to the City Wall; the canopy to radiation flux and interception coefficient were assumed as $0.85 \cdot 0.5^{(h/h_{\text{shade}})}$ (where h_{shade} is the shadow height on the wall surface and h is the height above the ground within the shadow range) and 0.8, respectively. Whereas in unshaded case, both of interception coefficients were 0.

The simulated surface temperatures and water content were compared with the measured results to validate the two-dimensional ‘City Wall–plant’ model.

3.2.1 Surface temperature

Fig. 5 shows the measured and simulated surface temperatures at shaded and unshaded $H_{3.9}$. Fig. 5a shows that simulated results agreed well with the measured results at shaded $H_{3.9}$ at Site 1. A linear regression analysis was performed with the measured and simulated results, and a good correlation was obtained with slope 0.98 and goodness-of-fit 0.98 ($y=0.976x$; $R^2=0.9871$; x : measured values, y : simulated values).

Fig. 5b shows the measured and simulated surface temperatures at the unshaded $H_{3.9}$ at Site 2. The simulation results agreed well with the measured values in summer but were slightly higher than the measured in winter. This is probably because the shade of the tree was not taken into consideration in

the simulation, despite that the solar altitude decreased in winter and the measured point was shaded by trees. Regardless, a linear regression analysis with the measured and simulated values at Site 2 shows good correlation between the simulated and measured temperatures, with goodness-of-fit of 0.92 and slope 1.03 ($y=1.0329x$; $R^2=0.9201$; x : measured values, y : simulated values).

3.2.2 Water content

Fig. 6 shows the simulated and measured water content at shaded $H_{0.15}$, $H_{1.2}$, and $H_{2.1}$ at Site 1. The simulation results show that the annual water content of $H_{0.15}$, $H_{1.2}$, and $H_{2.1}$ fluctuated within $0.15\text{m}^3/\text{m}^3$ – $0.25\text{m}^3/\text{m}^3$, 0 – $0.2\text{m}^3/\text{m}^3$, and 0 – $0.2\text{m}^3/\text{m}^3$. In early July, the water content of the points was higher due to the rain period; then, after the rain, the water content showed an obvious downward trend. Moreover, the water content at $H_{0.15}$, $H_{1.2}$, and $H_{2.1}$ in September to November (dry months) was fluctuating within $0.1\text{m}^3/\text{m}^3$ – $0.2\text{m}^3/\text{m}^3$, $0.05\text{m}^3/\text{m}^3$ – $0.1\text{m}^3/\text{m}^3$, 0 – $0.05\text{m}^3/\text{m}^3$, respectively. The simulation results could predict the fluctuation trend of the characteristic points on the wall surface subjected to rainfall. We analysed the consistency of measured and simulated values by using the mean absolute error (MAE) between the simulated and measured values at three heights, $H_{0.15}$, $H_{1.2}$, and $H_{2.1}$ was $0.029\text{m}^3/\text{m}^3$, $0.036\text{m}^3/\text{m}^3$, $0.035\text{m}^3/\text{m}^3$, respectively. The comparison between field and simulated data shows that the simulated water content was consistent with the measured result at three points and it can reproduce the time profile in the measured results.

It can be concluded that the simulated temperatures and water content agreed well with the measured results irrespective of shaded or unshaded

444 conditions. Thus, the proposed ‘City Wall–plant’
 445 model can be used to examine the influence of the
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446 surrounding trees on the hygrothermal fluctuations
 447 and weathering of City Wall.

Fig. 5 Comparison of measured and simulated surface temperatures: (a) Shaded H_{3,9}; (b) Unshaded H_{3,9}.

Fig. 6 Comparison of measured and simulated water content at three shaded points: (a) H_{0,15}; (b) H_{1,2}; (c) H_{2,1}.

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3.3 Calculated results

The surface temperatures, water content at the characteristic points (temperatures at H_{1,2}, H_{3,9}, H_{5,4}, and ground surface; water content at H_{0,15}, H_{1,2}, H_{2,1}, and ground surface) were calculated.

Fig. 7 shows the annual temperature fluctuations at points H_{1,2}, H_{3,9}, H_{5,4}, and ground surface in the shaded and unshaded cases. The temperature fluctuations in the unshaded case were larger than those in the shaded case, with large difference in maximum temperatures and small difference in minimum temperatures.

Statistics in Table. 1 show that compared with the unshaded case, the shaded surface showed smaller temperature fluctuations, and the difference of the maximum temperature between shaded and unshaded cases decreased with height. The maximum temperatures in the unshaded case was higher than those in the shaded case by 9.7 °C at H_{1,2}, 7.4 °C at H_{3,9}, 6.8 °C at H_{5,4}, and 11.8 °C at ground surface. The minimum temperatures in the unshaded case was lower than those in the shaded case by 0.8 °C at H_{1,2}, 0.5 °C at H_{3,9}, 0.5 °C at H_{5,4},

and 1.9 °C at ground surface. Compared with the unshaded surface, the shaded surface showed smaller temperature fluctuations with the minimum temperature increasing by 0.5 ~ 0.8 °C

Fig. 8 shows the water content at H_{0,15}, H_{1,2}, H_{2,1}, and ground surface between the shaded and unshaded cases. The water content in the shaded case was higher than that of the unshaded one including the ground surface. This is mainly due to the difference in the surface evaporation rate leading to water content differences at the same height. The water content decreased with height in both cases, except that the water content at unshaded points H_{2,1} and H_{1,2} was higher than that at point H_{0,15} in the rainfall period around 13th May and 31st July. Because of the heavy rainfall during this period (8.6 mm in 25 min (13th May); 10.6 mm in 45 min (31st July)), the bricks in unshaded case absorbed a large amount of rainfall. Then, the water content at H_{0,15} drained away faster than at H_{1,2} and H_{2,1}, as point H_{0,15} was close to the ground and the moisture conductivity of the soil was higher than that of brick. Statistics in Table. 2 shows that compared with the

unshaded case, the shaded surface showed smaller water content fluctuations, and smaller standard

deviation by around $0.04 \text{ m}^3/\text{m}^3$ at $H_{1.2}$ and ground surface.

Fig. 7 Comparison of simulated surface temperatures of points ($H_{1.2}$, $H_{3.9}$, $H_{5.4}$, and ground surface) between shaded and unshaded cases:

(a) Ground surface; (b) $H_{1.2}$; (c) $H_{3.9}$; (d) $H_{5.4}$

Table. 1 Statistics of simulated surface temperatures between shaded and unshaded cases.

		Unshaded (°C)	Shaded (°C)	Difference* (°C)			Unshaded (°C)	Shaded (°C)	Difference* (°C)
$H_{1.2}$	Max.	45.0	35.3	9.7	$H_{5.4}$	Max.	45.4	38.6	6.8
	Min.	-0.1	0.6	-0.8		Min.	-0.2	0.3	-0.5
	Ave.	19.3	17.6	1.7		Ave.	19.4	18.2	1.2
	Dev.*	9.9	8.7	1.3		Dev.*	10.0	9.0	1.0
$H_{3.9}$	Max.	45.4	38.0	7.4	Ground surface	Max.	46.0	39.6	6.3
	Min.	-0.2	0.3	-0.5		Min.	-2.3	-0.3	-1.9
	Ave.	19.4	18.2	1.3		Ave.	18.5	18.0	0.5
	Dev.*	10.0	9.0	1.1		Dev.*	10.77	8.59	2.2

*Difference=Unshaded values -Shaded values; Dev.=The standard deviation

Fig. 8 Comparison of water content at points $H_{0.15}$, $H_{1.2}$, $H_{2.1}$, and ground surface between shaded and unshaded cases.

Table. 2 Statistics of simulated water content between shaded and unshaded cases.

		Unshaded (m^3/m^3)	Shaded (m^3/m^3)	Difference* (m^3/m^3)			Unshaded (m^3/m^3)	Shaded (m^3/m^3)	Difference* (m^3/m^3)
$H_{1.2}$	Max.	0.278	0.293	-0.015	$H_{5.4}$	Max.	0.292	0.269	0.023
	Min.	0.005	0.138	-0.133		Min.	0.001	0.002	-0.001
	Ave.	0.131	0.201	-0.071		Ave.	0.041	0.066	-0.025
	Dev.	0.061	0.025	0.036		Dev.	0.048	0.052	-0.004
$H_{3.9}$	Max.	0.303	0.231	0.073	Ground surface	Max.	0.444	0.444	0.000
	Min.	0.001	0.004	-0.003		Min.	0.098	0.230	-0.132
	Ave.	0.051	0.102	-0.051		Ave.	0.246	0.332	-0.085

4 Discussion

In this study, the hygrothermal behaviour of an ancient city wall was evaluated by combining field measurements with numerical simulation,. Hygrothermal regulation via plantation/trees was achievable; the influence of urban trees on the sustainable protection of an ancient city wall (Nanjing City Wall) was quantitatively assessed .

4.1 The impact of trees on the freeze–thaw cycle of City Wall

To evaluate the impact of the trees/plantation on the freeze–thaw cycle of building elements (ancient City Wall of Nanjing as a point of reference), the ‘frequency’ and ‘duration’ of these phenomena were assumed as key evaluation indexes. ‘Frequency’ refers to the number of times the temperature crossed the freezing point 0 °C; ‘duration’ refers to the total time that temperatures remained below 0 °C in the year.

The freezing–thawing frequency and duration at heights of H_{1.2}, H_{3.9}, and H_{5.4} between shaded and unshaded cases were compared. It should be remarked that not all episodes of negative temperatures resulted in ice formation [42]. In this paper, 0 °C is used as the approximate critical value to count freezing events. Because the annual average outdoor temperature in 2019 was higher than that in a typical year, it is likely that the freezing–thawing cycles had less impact in 2019 than in a typical year. However, the influence of the trees was obvious. For a year, freezing events occurred five times with 5.4 hours of freezing at point H_{1.2} as well as six times with 13.9 hours at points H_{3.9} and H_{5.4} on unshaded surfaces, respectively, compared to no frost in the shaded case.

The freezing–thawing cycle is a threshold-driven process. Therefore, even a slight change to the wall microclimate can have significant consequences on frost-driven deterioration. The simulation of freezing–thawing cycles showed that the freezing–thawing frequency in the shaded case decreased compared with the unshaded. The decisive factors of the wall surface temperature are the solar radiation absorbed and nocturnal radiation emitted by the wall, which are influenced by the trees [43, 44]. The net radiation in the shaded case was larger

(small negative) at night, although less (small positive) during daytime than that in the unshaded case in the winter month (Feb.) (Fig. 10), which led to a higher minimum temperature in the shaded case. The water content also affects the temperature of the wall surface due to evaporative cooling. It can be seen from Table. 3 that the evaporation amount in the unshaded case was slightly higher than the shaded, which leads to more heat loss by evaporative cooling and lower temperatures in the unshaded case.

Considering the above-mentioned results, the evergreen trees can be judged to reduce the risk of freezing–thawing cycles.

4.2 The impact of trees on the salt crystallization risk of City Wall

The crystallization pressure of soluble salts is one of the most important deteriorating factors that affects the durability of porous materials [45, 46]. Salt decay includes the process of salt crystallization on the surface of a porous material (efflorescence) and the process of crystallization within the porous system (subflorescence) [47].

4.2.1 Salt crystallization (efflorescence)

The amount of evaporation is closely related to the amount of salt that migrates to the surface resulting in efflorescence if there is a source of salt.

Table. 3 shows the annual evaporation at heights (H_{1.2}, H_{3.9}, and H_{5.4}). The amount of annual evaporation in the shaded case was lower than the unshaded by 18% at H_{1.2}, 10% at H_{3.9}, and 8% at H_{5.4}. The monthly evaporation at three heights (H_{1.2}, H_{3.9}, and H_{5.4}) in shaded and unshaded cases is shown in Fig. 9. The monthly evaporation at three heights (H_{1.2}, H_{3.9}, and H_{5.4}) in unshaded case was greater than the shaded, except for point H_{1.2} in September, October, and November and points H_{3.9} and H_{5.4} in March and April. Table. 4 shows the monthly evaporation at the shaded point H_{1.2} was about 3% ~ 44% less than the unshaded from December to September, while 31% more in October and 67% more in November. This is mainly due to the higher temperature leading to rapid evaporation and a decrease in water content of bricks in the unshaded case. Due to the long-term drought from September to November, there was no water to make up for the loss from evaporation in

the unshaded case, whereas a relatively wet wall in the shaded case could provide more water for evaporation. The same condition happened in March and April at heights $H_{3.9}$ and $H_{5.4}$.

A large amount of evaporation took place in the unshaded case compared with the shaded case (Table. 3), meaning that there were higher possibilities of salt accumulation on the surface. In such a situation, it is likely that the trees can reduce efflorescence with their shade.

4.2.2 Crystallization within the porous system (subflorescence)

The crystallization pressure of soluble salts is one of the most important deteriorating factors that affect the durability of porous materials regarding the process of subflorescence [45]. Sodium sulfate is a destructive soluble salt existing often in porous materials; therefore, the risk of salt damage of the City Wall was studied with sodium sulfate. The sodium sulfate assumes a different phase depending on temperature and humidity, that is, sodium sulfate solution (liquid), thenardite (solid), and mirabilite (solid).

The impact of trees on the building wall (as City Wall Nanjing reference) deterioration risk from salt crystallization was evaluated using a phase diagram for sodium sulfate [46]. The daily average temperature and relative humidity at three heights $H_{1.2}$, $H_{3.9}$, and $H_{5.4}$ on the shaded and unshaded surfaces in the year of 2019 are plotted on the phase equilibrium chart in Fig. 11. The black lines divide the coordinate area into three parts: sodium sulfate

solution (liquid), thenardite (solid), and mirabilite (solid), corresponding to the phases of sodium sulfate under different temperature and humidity conditions. The phase change between liquid and solid or between solid (Mirabilite) and solid (Thenardite) can be related to crystallization pressure, which may adversely affect the structure of porous materials.

As seen in Fig. 11a, the lines that connect consecutive days are mostly located in a single phase (solution) for the shaded $H_{1.2}$, but located in three phases for the unshaded $H_{1.2}$. The unshaded case may lead to deterioration by salt crystallization, phenomenon with no serious risks for the shaded case. For the points $H_{3.9}$, $H_{5.4}$, the lines that connect consecutive days for both shaded and unshaded cases appear to be very similar. , this stands for the frequency of the connecting lines crossing the boundary between different phases, phenomenon that occurred significantly more frequently for the unshaded surface as compared to the shaded one. This reveals the higher probability of salt crystallization in the unshaded case compared to the shaded case, with the strongest influence at $H_{1.2}$ and the weakest at $H_{5.4}$, which indicate the influence of trees on reducing the risk of crystallization for the City Wall.

To evaluate the supersaturation and crystallization pressure, transient moisture (liquid and vapor) transfer and phase change processes of the salt and moisture must in detail be taken into consideration. This is a future work.

Fig. 10 Comparison of net radiation absorbed by the wall surface at three heights ($H_{1.2}$, $H_{3.9}$, and $H_{5.4}$).

(Net radiation= solar radiation - nocturnal radiation).

Table. 3 Comparison of annual evaporation at heights H_{1.2}, H_{3.9}, and H_{5.4}.

Total annual evaporation	H _{1.2}	H _{3.9}	H _{5.4}
Unshaded (kg/m ²)	236.9	203.1	202.8
Shaded (kg/m ²)	193.2	182.0	185.6
Percentage reduction*	18%	10%	8%

* Percentage reduction= (Unshaded – Shaded)/ Unshaded

Fig. 9 Comparison of monthly evaporation from the south-facing surface at heights H_{1.2}, H_{3.9}, and H_{5.4}.

Table. 4 Comparison of monthly evaporation at height H_{1.2}.

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Unshaded (kg/m ²)	9.9	5.8	24.1	18.1	31.6	29.0	27.1	37.3	19.5	12.3	11.3	10.9
Shaded (kg/m ²)	5.5	3.2	13.8	14.2	27.6	20.0	17.8	25.9	19.0	16.0	18.8	8.2
Percentage reduction * (%)	44	44	43	22	13	31	34	30	3	-31	-67	25

*Percentage reduction= (Unshaded – Shaded)/ Unshaded

Fig. 11 Plot of daily average temperature and humidity in shaded and unshaded cases: (a) H_{1.2}; (b) H_{3.9}; (c) H_{5.4}

4.3 The impact of characteristics trees

The comparison of simulated results indicated the influence of trees on surface microclimates of City Wall. The temperature and water content on the shaded surface showed less fluctuations as compared with the unshaded one. In addition, evergreen trees (Osmanthus) can effectively reduce the amount of evaporation, the risk of freeze–thaw cycles, and salt

crystallization on the shaded surface. Among the studied three heights, the lower part of City Wall was the optimum in terms of minimizing weathering risk. This is mainly due to the better shading effect of trees on the low part. It can be said that the shading effect of trees is positively correlated with the mitigation of weathering on the wall surface.

The shading effect of trees is closely related to the canopy structure and tree speciation. The efficacy of

tree shading has been previously investigated involving different tree species with specific characteristics such as leaf size and leaf area index (LAI) [48]. It was found that trees with large leaves or a large leaf area index could provide with better shading [49], as expected. In addition, trees can be categorized into evergreen and deciduous trees. As deciduous trees in winter may have the similar effect with the unshaded case, it can be assumed that deciduous trees are less effective than evergreen trees in mitigating surface weathering of City Wall.

Except of the hygrothermally regulated beneficial for the heritage result, due to the tree leaves and branches, root growth also bears potential risks rendering the heritage vulnerable [50]. Therefore, a comprehensive risk assessment of the potential buildings' deterioration and trees' protection must be undertaken prior plant management activities and interventions in heritage sites.

5 Conclusion

This study, by involving actual physicochemical measurements and simulation intended to examine the influence of trees on the conservational status and the surface weathering of heritage sites. The City Wall of Nanjing, China was used a point of reference.

(1) The impact of trees on the hygrothermal characteristics of the wall's surface was preliminarily evaluated via actual field measurements. The measured results revealed that the trees weaken the thermal stress on the wall.

(2) To evaluate the impact of the trees on the surface weathering of the City Wall, a 'City Wall-plant' model was developed and trialled. The good agreement between actual-validation data and the ability of the model to respond to diurnal and seasonal variations proved the robustness of the model.

(3) The impact of trees on the surface weathering of the City Wall was examined using the proposed

model. Compared with the unshaded surface, the shaded surface exhibited i) smaller temperature fluctuations with the minimum temperature increasing by 0.5 ~ 0.8°C, ii) smaller water content fluctuations with the standard deviation decreasing by 0 ~ 0.04 m³/m³.

In addition, the shaded case showed that evergreen trees can effectively reduce the evaporation rate by 8~18%, and the risk of deterioration due to efflorescence, subflorescence, and freeze-thaw cycles on the wall surfaces.

(5) Deciduous trees in winter, may have a similar shading effect with that evaluated at the unshaded case. Hence, the deciduous trees are supposed to be less effective than the evergreen ones in mitigating surface weathering.

By conducting this study, we found that the trees have a significant influence on the microenvironment and a positive effect in buffering the surface weathering of the cultural heritages. This study provides a basis for the landscape design around the City Wall, and presents promising possibility for more environmentally sustainable approaches to the conservation of exposed and immovable historical sites.

Declaration of Competing Interests

The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Appendix A. Nomenclature

Nomenclature

R_v	the gas constant of water ($R_v = R/M_v$)
R	the universal gas constant [Pa·m ³ /kmol·K]
M_v	molar weight of water [kg/kmol]
h	the relative humidity.
ρ_w	water density [kg/m ³]
Ψ	the volumetric water content [m ³ /m ³]
n	unit vector in the direction of gravity
q	heat flux [W/m ²]

c_p	specific heat capacity [J/(m ³ K)]
c'_a	moisture capacity of the air [kg/(m ³ Pa)]
V	volume [m ³]
ρ	density [kg/m ³]
β	evaporation efficiency of vegetation [-]
C_h	coefficient of volume movement [-]
U	wind speed [m/s]
S_h	specific humidity [kg/kg]

j	total (liquid and vapor) water flux [kg/(m ² ·s)]	S	area[m ²]
T	temperature [K]	r	heat of phase change of water [J/kg]
p	vapor pressure [Pa]	g	gravitational acceleration [=9.8m/s ²]
p_{sat}	saturation vapor pressure [Pa]	E_p	rainfall trapped by trees [kg/(m ² s)]
μ	water chemical potential [J/kg]	E_t	evapotranspiration of plants [kg/m ² s]
γ	transmission coefficient of solar radiation by canopy [-]	E_m	evaporation from material (wall or ground) surface [kg/m ² s]
γ'	transmittance of plants to rainwater [-]	$q_{sol,c}$	solar radiation absorbed by trees[W/m ²]
A	absorption coefficient of solar radiation [-]	$q_{noc,c}$	nocturnal radiation of trees[W/m ²]
ε	longwave emissivity [-]	$q_{lat,c}$	latent heat of evapotranspiration[W/m ²]
α	heat transfer coefficient [W/(m ² ·K)]	$q_{sol,m}$	solar radiation absorbed by material (wall or ground) surface[W/m ²]
α'	water vapor transfer coefficient [kg/m ² sPa]	$q_{noc,m}$	nocturnal radiation of material (wall or ground) surface[W/m ²]
α'_μ	water vapor transfer coefficient under the gradient of water chemical potential [kg/m ² ·s·(J/kg)]	$q_{lat,m}$	latent heat of evaporation from material (wall or ground) surface[W/m ²]
α'_T	water vapor transfer coefficient under the gradient of temperature [kg/m ² ·s·K]		
λ'_μ	water (liquid and vapor) conductivity under the gradient of water chemical potential [kg/m·s·(J/kg)]		
λ'_T	water (liquid and vapor) conductivity under the gradient of temperature [kg/m·s·K]		
λ'_{Tg}	Water vapor conductivity of the solid material under the gradient of temperature [kg/(m·s·K)]		
$\lambda'_{\mu g}$	Water vapor conductivity under the gradient of water chemical potential [kg/(m·s·(J/kg))]		
λ	thermal conductivity [W/m·K]		
I_s	solar radiation [W/m ²]		
I_n	nocturnal radiation [W/m ²]		
P_r	precipitation [kg/(m ² s)]		
P_{r_m}	the rainfall to ground [kg/m ² s]		
R	thermal resistance [(m ² K)/W]		
R'	moisture resistance [(m ² ·K·Pa) / kg]		

Subscripts

a	air
o	outdoor
s	surface
c	canopy
as	air space
m	material (wall or ground)
sol	solar radiation
noc	nocturnal radiation
lat	latent heat
ex	air exchange
oc	the outdoor air -canopy surface
ca	the canopy-air space surface
am	the air space-material (wall or ground) surface

Appendix B. Plant model

The plant model was based on the plant model by Kondou [41]. The equations of heat and moisture balance in plant model are as follows:

- Heat balance of the canopy cell:

$$(cp)_a \cdot V_c \cdot \frac{\partial T}{\partial t} = \left\{ \frac{(T_o - T_c)}{(1/\alpha_{oc} + R_c)} + q_{sol,c} - q_{noc,c} - q_{lat,c} - \alpha_{ca} \cdot (T_c - T_{as}) \right\} \cdot S + q_{ex,c} \quad (B.1)$$

Where,

$$q_{sol,c} = I_{sol} \cdot (1 - \gamma) \cdot A_c \quad (B.2)$$

$$q_{lat,c} = r \cdot (E_t + E_p) \quad (B.3)$$

$$q_{noc,c} = \varepsilon_c \cdot I_{noc} \quad (B.4)$$

- Heat balance of the air space under the canopy:

$$(cp)_a \cdot V_{as} \cdot \frac{\partial T}{\partial t} = \alpha_{ca} \cdot (T_c - T_{as}) \cdot S - \sum_1^{m1} \alpha_{am} \cdot (T_{as} - T_{m,i}) \cdot S_i + q_{ex,as} \quad (B.5)$$

- Moisture balance of the canopy cell:

$$C'_a \cdot V_c \cdot \frac{\partial p}{\partial t} = \left\{ \frac{(p_o - p_c)}{(1/\alpha'_{oc} + R'_c)} + E_p + E_t - \alpha'_{ca} \cdot (p_c - p_{as}) \right\} \cdot S + j_{ex,c} \quad (B.6)$$

- Moisture balance of the air space under the canopy:

$$C'_a \cdot V_{as} \cdot \frac{\partial p}{\partial t} = \sum_1^{m2} E_{m,i} \cdot S_i + j_{ex,as} \quad (B.7)$$

Where,

$$E_t = \rho \beta C_h U \cdot \left(\frac{\partial S_h}{\partial P} \right) \cdot (p_{sat}(T_c) - p_o) \quad (B.8)$$

$$E_p = (1 - \gamma') \cdot P_r \quad (B.9)$$

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