Estimation of thermal hazards in surrounding rock of subway tunnel under dual periodic temperature boundaries: a case study

Wei Liu1,2 · Shufei Liang1 · Qingwei Huang1 · Yueping Qin1

Received: 14 October 2021 / Accepted: 15 April 2022 / Published online: 5 May 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
Thermal hazards of the surrounding rock of subway tunnels are becoming apparent, in which the heat transfer in the surrounding rock plays a crucial role. Due to the shallow buried depth, the subway tunnel encounters a more complicated heat exchange under the duplicate effects of periodic temperature fluctuation of ground atmosphere and periodic temperature variation of tunnel wind, but this issue has not been fully addressed. In this work, a transient heat transfer model of tunnel surrounding rock based on dual periodic temperature boundaries was established. A solver was developed to estimate the temperature rise and heat transfer of surrounding rock. The correctness of this model was then verified by comparing with previous empirical values and semi-empirical equations. The results show that the temperatures of the surrounding rock at different depths still fluctuate following the simple harmonic waves, and there are some regions that are heavily affected by the duplicate effects, such as the overlying strata of the tunnel. The surrounding rock generally exhibits heat storage in annual cycle, but the total heat storage decreases year by year until it tends to stabilize. Furthermore, the shallower the tunnel is buried, the greater the influence of ground temperature and the higher the temperature rise in the tunnel surrounding rock. This research provides an alternative approach to determine the heat storage of tunnel surrounding rock and evaluates the process of thermal disaster manifestation of subway.

Keywords Subway tunnel · Thermal hazards · Periodic boundary · Heat transfer · Dual periodicity

Introduction

Subway has become a widely used means of transportation in the world. A long-term operation of the train will generate a lot of heat, resulting in a gradual increase in the temperature of the tunnel surrounding rock and wind flow, and the thermal hazards gradually become apparent (Zhang and Li 2020). The heat accumulation in the London subway has caused the tunnel temperature to rise from 16 °C in the early 1900s to over 30 °C today (Tong et al. 2019). In Hong Kong, the subway had to cool the tunnel cave with seawater in winter to cope with the inadequate design of environmental control (Ji et al. 2001). For Beijing Metro Line 1, its air temperature in summer had already exceeded 28.5 °C, and still rose at a rate of 0.2 °C per year (Tong 2005). High tunnel temperatures not only cause discomfort to passengers, but also affect the safe operation of the trains (Ampofo et al. 2004a). When the tunnel air temperature is so high that the inlet temperature of the condenser exceeds 45 °C, the train’s air conditioner will not be able to turn on the power, thus causing operational hazards (Bogdanovská et al. 2019). Therefore, more attention should be paid to the thermal hazards of subway tunnel.

Currently, research on thermal hazards control in tunnels has mainly focused on the extraction and utilization of tunnel heat, optimization of ventilation networks and upgrading of environmental control systems, etc., but the function of tunnel surrounds in regulating the thermal environment of tunnels has rarely been addressed (Insana and Barla 2020; Li et al. 2015; Ogunleye et al. 2020; Tong et al. 2020; Zhang et al. 2017). In fact, the surrounding rock of the tunnel can
absorb or release considerable heat to adjust the temperature of airflow in tunnels (Revesz et al. 2016; Wang et al. 2017; Zhang et al. 2017). There have been a number of investigations about the heat transfer of surrounding rocks carried out in the fields of mine thermal disaster, tunnel freezing damage in cold area, underground storage freezer, and ground source heat pump (Qin et al. 2015b; Revesz et al. 2016; Unver and Agan 2003; Yu et al. 2018), but rarely involves the subway tunnel. It is crucial to investigate the heat transfer of surrounding rock of subway tunnel for the thermal hazard’s prevention.

Most of China’s subways are buried 5 to 10 m underground. Due to the shallow burial depth, the heat transfer of surrounding rock of subway tunnel is greatly affected by the ground temperature, while the temperature of the ground-level atmosphere varies considerably from season to season (Li et al. 2011). For example, the temperature difference of the ground between summer and winter in Beijing may reach 50 °C. Seasonal variation needs to be considered in the thermal disaster control of the subways. Changes in the ground-level atmospheric temperature directly result in temperature fluctuations of the surrounding rock above the tunnel, and the airflow in the tunnels acquired from the ground atmosphere also exhibits correspondingly pronounced annual cycle temperature variations. The synergistic effect of these two temperature fluctuations complicates the heat transfer mechanism of the surrounding rock of the tunnel (Barla et al. 2016; Feng et al. 2016; Tan et al. 2014). On the other hand, the heat exchanges between the surrounding rock and tunnel airflow are also different against the seasons. In summer, the ground-level atmospheric temperature and the tunnel wind temperature are both higher than the average temperature of the tunnel wall surface. As the hot air flows through the tunnel, the surrounding rock absorbs part of the heat. However, the surrounding rock may release some heat into the airflow in winter due to its average wall temperature slightly higher than the tunnel air temperature (Jenkins et al. 2014). Thus, whether the tunnel surrounding rock stores heat or dissipates heat depends on the seasonal variations, and the determination of this part of heat load is very important in the treatment of thermal disaster of subways.

Numerical calculation is one of the major approaches to investigate the thermal disaster of subways. In 1975, the software of subway environment simulation (SES) had been developed by the USA (Transportation 1975), which was applied to the design of underground HVAC systems in Atlanta, New York, Hong Kong, etc., but this software could not get the spatial temperature distribution due to its basis on Bernoulli equation and pipe network theory (Ke et al. 2002). A specialized software system called STESS (Wang and Li 2018) was developed in China since 1979 to simulate the piston wind effect during train running and the influence of heat storage in the tunnel overburden on the thermal environment. Furthermore, Zhang and Wang presented a kind of two-dimensional unsteady heat transfer model of the tunnel surrounding rock, but the influence of periodic ground temperature fluctuations was not included in their analysis (Wang and Li 2018; Zhang and Li 2018, 2019). Hu et al. had adopted FLAC-3D to simulate the effects of main factors such as thermal properties of the soil and initial ground temperature on the range of heat transfer in the tunnel surrounding rock (Hu et al. 2008). Krasyuk et al. investigated the range of thermal regulation of the surrounding rocks of the subway tunnel and showed that the shallow subway tunnels were affected up to 15-m depth (Krasyuk et al. 2015). Li et al. had measured the tunnel air temperature and wall temperature of Nanjing Metro Line 1 and concluded that the heat absorbed by the tunnel surrounding rock accounted for about 7.5% to 26.6% of the total heat generation (Li et al. 2012). Nevertheless, the researchers had rarely considered the convective heat transfer between the surrounding rock and tunnel wind at such complex dual-period temperature boundaries.

In this work, a mathematical model of temperature field of surrounding rock of subway tunnel was established by combining the periodic ground temperature boundary and the periodic tunnel wind temperature boundary (Qin et al. 2013; Qin et al. 2015a; Qin et al. 2015b). The numerical analysis was then carried out through an example to estimate the heat storage and temperature rise of tunnel surrounding rock. These calculation results provide a reference for the thermal hazards control in subway tunnels.

### Model of surrounding rock temperature field of subway tunnel

Subway tunnels are usually divided into open-cut tunnels (i.e. rectangular tunnels) and shield tunnels according to different construction techniques (Jin et al. 2018; Shi et al. 2017; Xu et al. 2019a). Generally, the open-cut is used to construct the shallow tunnels. Many subway tunnels in China belong to these shallow underground structures, so the ground-level temperature has a great influence on them. Therefore, the rectangular tunnel is selected as the research object (Pitilakis 2009; Xu et al. 2019b).

There are some assumptions that need to be clarified: (i) the tunnel surrounding rock is homogeneous and isotropic with no internal heat source, and its thermal conductivity uses the average value of the thermal conductivity of all rock layers; (ii) the temperature difference and heat flux along the tunnel axis are neglected; (iii) the effect of train running on the heat exchange of tunnel wall is not considered in modeling; (iv) the initial temperature of the surrounding rock is set as the temperature of the soil thermostat layer that is close to the annual average temperature of the ground (Jin...
et al. 2012; Sun et al. 2013; Zhang and Li 2018); (v) the effects of daily cyclic temperature fluctuations and weather variations are ignored. In this way, the temperature field of the tunnel surrounding rock can be simplified into a two-dimensional unsteady model.

**Integral equation of heat transfer of surrounding rock**

The change of temperature field of tunnel surrounding rock belongs to the category of physical thermal conduction, and its integral equation expresses as (Xiaozhao et al. 2012):

$$\int_S \rho c \frac{\partial T}{\partial t} dS + \int_l \lambda \frac{\partial T}{\partial n} dl = 0$$  \hspace{1cm} (1)

where $\rho$ is the density of surrounding rock, kg/m$^3$; $c$ is the specific heat capacity of surrounding rock, J/(kg °C); $T$ is the temperature of surrounding rock, °C; $n$ is the outward normal direction; $\lambda$ is the thermal conductivity, W/(m °C); $t$ is time, s; $S$, $l$ are the boundary and area of the integration region, m$^2$, m.

**Dual periodic temperature boundaries**

Figure 1 shows a cross section of surrounding rock of a rectangular tunnel. It can be found that there are three boundaries for the above model: ground-level boundary, tunnel wall boundary and the deep boundary of surrounding rock, which are named $\Gamma_1$, $\Gamma_2$ and $\Gamma_3$, respectively. Figure 2 further illustrates the ground-level atmospheric temperature variation in Suzhou City referring to the weather data of the past 3 years from the National Meteorological Center of China. This indicates that the annual variation of the ground atmospheric temperature can be viewed as a complete simple harmonic. The airflow in the tunnel from the ground atmosphere should correspondingly change in another simple harmonic form (Adil Zainal and Yumruta 2015; Jun et al. 2017; Strub et al. 2005; Wang et al. 2014). Their sinusoidal equations are expressed as:

$$\begin{align*}
T_{f_1} &= \bar{T}_{f_1} + A_{f_1} \sin \left( \frac{2\pi t}{\tau} + \varphi_1 \right) \\
T_{f_2} &= \bar{T}_{f_2} + A_{f_2} \sin \left( \frac{2\pi t}{\tau} + \varphi_2 \right)
\end{align*}$$  \hspace{1cm} (2)

where $T_{f_1}$, $T_{f_2}$ are the ground-level temperature and the tunnel air temperature, °C; $\bar{T}_{f_1}$, $\bar{T}_{f_2}$ are the average values of the sine waves, °C; $A_{f_1}$, $A_{f_2}$ are the amplitudes of the ground surface temperature and tunnel wind temperature, °C; $\tau$ is the annual period, s; $\varphi_1$, $\varphi_2$ are the phase angle.

The computational region is shown in Fig. 1. The ground boundary and the tunnel wall boundary are the convective heat transfer boundaries (Yuan et al. 2017). The deep boundary of surrounding rock can be set as the original rock temperature. Assuming that the convective heat transfer coefficients are constant, combined with Eq. (2), the boundary conditions of the temperature field of tunnel surrounding rock are expressed as (Dong et al. 2019):

$$\begin{align*}
-\lambda \frac{\partial T}{\partial n} \bigg|_{\Gamma_1} &= \alpha_1 (T_{\Gamma_1} - T_{f_1}) \\
-\lambda \frac{\partial T}{\partial n} \bigg|_{\Gamma_2} &= \alpha_2 (T_{\Gamma_2} - T_{f_2}) \\
T \bigg|_{\Gamma_3} &= T_0
\end{align*}$$  \hspace{1cm} (3)

where $\alpha_1$, $\alpha_2$ are the convection heat transfer coefficients of boundary $\Gamma_1$ and $\Gamma_2$, W/(m$^2$ °C); $T_{\Gamma_1}$, $T_{\Gamma_2}$ are the temperatures of ground boundary and the tunnel wall boundary, °C; $T_0$ is the original rock temperature, °C.

Equations (1) and (3) constitute the mathematical model of the temperature field of surrounding rock under the superposition of periodic ground temperature boundary and periodic tunnel wind temperature boundary.
Simulation calculations

Numerical example

In this work, the tunnel surrounding rock of a section of Suzhou Metro Line 2 in China was selected as an example for numerical investigation. The rectangular tunnel was 4.4 m wide and 5.16 m high. The convective heat transfer coefficients in the wall surfaces of the tunnel were set with reference to previous research results, and the convective heat transfer coefficients of the ground surface were based on the local outdoor wind studies (OU et al. 2002; Zhang and Li 2018). The surrounding rock layers are mainly sandstone, and their thermophysical properties were shown in Table 1 (Li et al. 2019; Liang and Zhao 2011; Zhang et al. 2013). The ground temperature fluctuation of Suzhou City used the atmospheric data shown in Fig. 1, but the solar radiation was ignored. The tunnel air temperature cited in the on-site data in Re. (Jiang 2018) that had measured the air temperature variation in the tunnel of the Suzhou Metro Line 2. It is assumed that the phase angles of the ground atmospheric temperature wave and the tunnel wind temperature wave are both zero at the first iteration. The periodic variations of the air temperature in tunnel and near the ground were determined as follows:

\[
\begin{align*}
T_{f1} &= 16 + 21 \sin(2\pi t/\tau) \\
T_{f2} &= 22 + 5.5 \sin(2\pi t/\tau)
\end{align*}
\]

(4)

The above equations indicate that the tunnel wind temperature is greatly different from the ground atmospheric temperature. Due to the relatively closed environment for the underground tunnel, many heat sources such as train operation, power consumption, air conditioner, and the heat transfer of surrounding rock will release large amounts of heat into the tunnel airflow, which greatly increases the air temperature in the tunnels (Tan et al. 2014; Zhang et al. 2016).

Grid division and solving

A suitable meshing is the premise for calculating the temperature field of surrounding rock. Due to a strong adaptability to the irregular calculative region around the tunnel as shown in Fig. 1, the triangular cell was used to solve the mesh division. Considering that the temperature variations close to the tunnel wall and the ground were drastic, the closer to these two areas, the finer the mesh, but the deeper into the surrounding rock, the rougher the mesh, shown in Fig. 3. The physical model was divided into 1684 nodes and 3200 cells. Such a gradually expanding meshing greatly improved the accuracy and speed of the calculations. Based on the triangular mesh, the temperature field model was discretized by the finite volume method (Liu and Qin 2017), and we developed independently a solver to calculate this discrete model. The iteration time was incremented at equal intervals, and the step time was calculated by 1/10,000 of the annual period. The temperature of all nodes calculated at the previous moment was used as the initial condition for calculating the temperature of the nodes at the next moment. Finally, the temperature data of all nodes were output at the set time.

Results and analysis

Temperature variation of surrounding rock section

Figure 4 represents the comparison results of temperature distribution of tunnel surrounding rock among the 2nd, the 5th and the 10th year after ventilation when the buried depth

Table 1 Thermophysical properties of surrounding rock of subway

| Symbol                        | Value | Unit       |
|-------------------------------|-------|------------|
| Average thermal conductivity  | \( \lambda \) | 1.84 W/(m °C) |
| Average density               | \( \rho \) | 2250 kg/m³ |
| Average specific heat capacity | \( c \)  | 0.84 J/(kg °C) |
| Convection heat transfer coefficient of ground | \( \alpha_1 \) | 5 W/(m² °C) |
| Convection heat transfer coefficient of tunnel | \( \alpha_2 \) | 10 W/(m² °C) |
| Original rock temperature     | \( T_0 \) | 16 °C |

Fig. 3 Schematic diagram of grid division of tunnel section
Fig. 4 Temperature field distributions of tunnel surrounding rock when buried 5m deep
of tunnel roof is 5 m. Four equidistant moments in one annual cycle, i.e. \( t = k\tau/4 \) (\( k = 1, 2, \ldots, N \); \( \tau \) is the annual cycle; the abscissa between 0 and 1 is defined as the first year), are selected to intuitively display the temperature distribution in the typical days of the four seasons. In this figure, we can find that the periodic ground-level temperature wave has a limited effect on the underground depth, about \(-11\) m, and this effect depth has not increased much even after 10 years, while the influence range of the periodic tunnel wind temperature wave on the surrounding rock mass is larger and larger over time. There are some regions affected by the duplicate effects of these two periodic temperature waves, such as the region above the roof of the tunnel. The effects are most prominent in autumn, resulting in a higher temperature in this region.

In fact, the temperature wave can transmit from the ground into the surrounding rock mass below. When encountering the temperature wave of the tunnel wind, these two waves are superposed on each other and affect the temperature distribution around the tunnel. Predictably, the shallower the tunnel is buried, the stronger these effects will be.

**Temperature variation of tunnel wall surface**

Figure 5 illustrates the temperature variations of three monitoring points on tunnel wall surface over time, in which the monitoring point A was set at the midpoint of the tunnel roof, the point B at the midpoint of the left sidewall, and the point C was placed at the midpoint of the tunnel floor, shown in Fig. 1. As can be seen in Fig. 5a, the temperature of the monitoring point A also generates periodic fluctuation in the form of a simple harmonic wave. This wave is closer to the periodic tunnel wind temperature wave in amplitude and wavelength, but the former lags behind slightly. It indicates that the temperature wave of the tunnel wind plays a major role in influencing the tunnel wall temperature, while the ground-level temperature still slightly changes the temperature fluctuation of the tunnel roof. Otherwise, the temperature wave of point A will coincide with the wind temperature wave after a long time of ventilation. The extreme point A of the temperature wave lies in the range of the ground-level temperature influence, which is slightly below the peak value of the tunnel wind temperature in winter, and the large temperature difference between the surface atmosphere and the tunnel wind flow in winter is responsible for this phenomenon. It is foreseeable that this effect will be more pronounced when the tunnel depth is shallow enough, but gradually disappears as the buried depth increases. Furthermore, Fig. 5b shows the comparison results of temperature changes of these three monitoring points. It can be seen that (i) the temperature fluctuation of the tunnel roof is obviously higher than that of floor or sidewall, but the roof temperature wave is relatively lagging; (ii) the temperature curves of the sidewall and the floor are basically coincident, indicating that the ground temperature fluctuation has little effect on these areas.

**Temperature waves in the surrounding rock mass**

Figure 6 manifests the variations of temperature waves in the surrounding rock mass at different depths above and below the tunnel, where the monitoring point 1 was set at the ground, the point 2 at 2.5 m deep, and the point 3 was arranged at 17 m deep, shown in Fig. 1. It can be seen that the temperature waves have hysteresis at various layers between the ground and the tunnel wall. The further away from the ground or the tunnel wall, the greater the temperature wave
Estimation of thermal hazards

Estimates of temperature increase in the surrounding rock

Figure 8 shows the temperature distribution on the vertical symmetry axis of the tunnel surrounding rock section at a buried depth of 5 m and 11 m in summer. It can be seen that the temperature in the upper part of the tunnel is almost unchanged over time, even after 30 years, but the temperature of the rock at the tunnel floor will increase significantly. Along this vertical symmetry axis, the temperatures at different nodes are weighted and averaged, so the temperature rise of the surrounding rock mass can be roughly evaluated by comparing it with the original rock temperature, as shown in Table 2. Taking the buried depth of 5 m as an example, the surrounding
rock mass has increased by about 7.5 °C in 30 years. The general rule is that the shallower the tunnel buried depth, the greater the temperature rise of the surrounding rock mass and the greater the thermal hazard.

**Heat flow of tunnel wall**

In this work, the mesh of the tunnel wall had been appropriately densified to improve the calculation accuracy. The rectangular tunnel wall was divided into $N$ elements, and the temperature of each node was expressed in terms of $T_1, T_2, T_3, \ldots T_N$, in which the length between two adjacent nodes was marked in terms of $L_1, L_2, L_3, \ldots L_n$, and the total length was $L$.

The average value method was used to calculate the average temperature of the tunnel wall, which was related to the calculation of heat transfer quantity of surrounding rock, as follows:

$$T_w = \frac{\sum_{i=1}^{n-1} \left( T_i + T_{i+1} \right) L_i + \frac{T_n + T_1}{2} L_n}{L} \quad (5)$$

where $T_w$ is the average temperature of the tunnel wall, °C; $T_i$ is the temperature of each node, °C; $L_i$ is the length between two adjacent nodes, m; $L$ is the total length, m.

The heat flux on the tunnel wall should be imported or exported periodically under the dual periodic variation boundaries. According to Fourier’s law, the heat flux on the tunnel wall can be expressed as (Alkhaier et al. 2012):

$$\begin{cases} 
q_+ = \alpha (T_f - T_w) & T_f > T_w \\
q_- = \alpha (T_f - T_w) & T_f < T_w 
\end{cases} \quad (6)$$

where $T_f$ is the fluid temperature, °C; $q_+$ is the heat flux that the surrounding rock absorbs heat from the wind, W/m²; $q_-$ is the heat flux that the surrounding rock releases heat into the wind, W/m².

Figure 9 reveals the variations of wind temperature, average wall surface temperature, and heat flux of wall surface when buried 5m deep. As can be seen, the temperature of tunnel wind rises steadily from spring to summer, with the highest in summer. In this process, the wind temperature is higher than the average temperature of wall surface, so the wind flow continuously transfers the heat into the surrounding rock mass. On the other hand, the wind temperature continuously decreases from autumn to winter, but it is lower than the wall surface temperature. At this time interval, the surrounding rock mass releases heat into the wind flow. It can be found that the heat absorption and heat dissipation are not strictly balanced, while the heat storage is greater than the heat dissipation. Moreover, it can also be seen that the wind temperature wave reaches the extreme value $\eta$ days before the wall temperature wave, and the wall heat flux wave reaching its extreme value is $\varepsilon$ days ahead of the wall temperature wave. These two time differences actually represent the differences of phase angles between the waves. The corresponding results are shown in Table 3. It indicates that the buried depth of tunnel has a large influence on these two differences of phase angles. A shallower buried depth corresponds to the larger phase angle differences, but these effects disappear when the depth is more than 11 m.

**Heat transfer quantity of surrounding rock**

The heat transfer on tunnel wall surface can be calculated through integrating heat flux with time. The heat absorption quantity per unit area $\overline{Q}_+$, kJ/m²) and heat dissipation quantity per unit area $\overline{Q}_-$, kJ/m²) of the tunnel surrounding rock in the $N$th year can be obtained as (Gow et al. 2018):

$$\begin{cases} 
\overline{Q}_+ = \int_{t_1}^{t_2} \alpha_2 (T_f - T_w) \, dt \\
\overline{Q}_- = \int_{t_2}^{t_3} \alpha_2 (T_f - T_w) \, dt 
\end{cases} \quad (7)$$

| Depth (m) | Temperature rise (°C) |
|-----------|------------------------|
|           | The 2nd year | The 5th year | The 10th year | The 20th year | The 30th year |
| 5         | 6.02        | 6.44         | 6.89          | 7.32          | 7.49          |
| 7         | 5.60        | 5.89         | 6.17          | 6.55          | 6.70          |
| 11        | 4.20        | 4.49         | 4.81          | 5.15          | 5.28          |
| 15        | 3.96        | 4.23         | 4.54          | 4.92          | 5.07          |

![Figure 9](image-url) Variations of wind temperature, average wall surface temperature and heat flux when buried 5 m deep
where $t_1$ and $t_2$ are the endothermic time interval in the $N$th year, shown in Fig. 8, s; $t_2$ and $t_3$ are the cooling interval, s.

The calculated results of heat absorption and dissipation are shown in Table 4 (a) and (b). The $r$ is defined as the ratio between absorption and dissipation, i.e. the absolute value of heat absorption divided by heat dissipation, and the results are shown in Table 5. We can see that the annual heat absorption is much greater than the heat dissipation. Heat absorption decreases year by year, while the heat dissipation increases. The $r$-value is also on the decrease over year. All of them tend to stabilize after 20 years of tunnel ventilation, and then the tunnel surrounding rock enters a relatively stable stage of heat storage.

Sum $\bar{Q}_{+}$ and $\bar{Q}_{-}$ to get the total heat storage per unit area $\bar{Q}_0$ of the surrounding rock mass in different years, as shown in Table 6.

Figure 10 illustrates the total heat storage capacity of the surrounding rock under dual periodic temperature boundaries as the burial depth of tunnel increases. It can be seen that the total heat storage per unit area of the tunnel is the largest at the first year after the ventilation, and then gradually decreases, in which the decreasing amplitude becomes smaller and smaller. For example, when the buried depth of tunnel roof is 5m, the total heat storage reached $7.51 \times 10^4$ kJ/m$^2$ (2.38 W/m$^2$) at the second year, but it drops to $6.68 \times 10^4$ kJ/m$^2$ (2.12 W/m$^2$) at the 10th year. The sudden change in heat storage of the surrounding rock at the 2nd year is the result of the initial temperature of the tunnel surrounding rock being assumed to be constant. From the second year onwards, the shallower the buried depth, the more heat is stored. This result originates from the effects of the periodic temperature fluctuation on the ground.

Moreover, some subway designs had used the summer value ranging from 6.3 to 12.6 W/m$^2$ to fix the heat absorption quantity of tunnel surrounding rock (Xu 2002), while our calculation values are slightly lower than that range. In fact, our calculated results had taken into account the total heat absorption throughout year under the effects of dual periodic temperature boundaries, which should certainly be lower than that only considering summer, but our summer peak about 8.4 W/m$^2$ is within the above range. This indicates that our calculation data is more accurate and reliable, thus verifying the dual periodic model, but also shows that these subways had exaggerated the heat storage capacity of surrounding rock in the thermal environment control or thermal disaster prevention.

### Comparison of heat transfer models

There are some empirical equations of heat absorption of tunnel surrounding rock proposed in the previous literature. We had collected two typical semi-empirical models and compared them with our proposed model.

Model 1 (Mao and Liu 1993):

| Depth (m) | $\bar{Q}_{+}$ ($10^4$ kJ/m$^2$) | The 1st year | The 2nd year | The 5th year | The 10th year | The 15th year | The 20th year | The 25th year | The 30th year |
|----------|---------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 3        | 13.46                           | 10.56        | 10.30        | 10.09        | 9.94         | 9.88         | 9.86         | 9.85         |
| 5        | 13.26                           | 10.36        | 10.05        | 9.81         | 9.66         | 9.61         | 9.54         | 9.50         |
| 7        | 13.30                           | 10.08        | 9.76         | 9.57         | 9.42         | 9.37         | 9.34         | 9.32         |
| 11       | 13.43                           | 9.08         | 8.65         | 8.39         | 8.24         | 8.17         | 8.13         | 8.10         |
| 15       | 13.65                           | 8.79         | 8.17         | 7.86         | 7.70         | 7.66         | 7.60         | 7.57         |

| Depth (m) | $\bar{Q}_{-}$ ($10^4$ kJ/m$^2$) | The 1st year | The 2nd year | The 5th year | The 10th year | The 15th year | The 20th year | The 25th year | The 30th year |
|----------|---------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 3        | −1.54                           | −1.63        | −1.74        | −1.82        | −1.89        | −1.97        | −1.99        | −2.00        |
| 5        | −2.72                           | −2.85        | −3.01        | −3.13        | −3.21        | −3.28        | −3.31        | −3.32        |
| 7        | −3.09                           | −3.21        | −3.39        | −3.50        | −3.57        | −3.64        | −3.66        | −3.67        |
| 11       | −2.51                           | −2.77        | −3.00        | −3.15        | −3.22        | −3.29        | −3.32        | −3.32        |
| 15       | −2.04                           | −2.25        | −2.83        | −3.02        | −3.09        | −3.16        | −3.19        | −3.20        |
where $q_1$ is the heat absorption of surrounding rock of the Model 1, W/m$^2$; $\Delta T$ is the temperature difference between tunnel wind flow and the original rock temperature, °C; $\alpha$ is the convection heat transfer coefficient of tunnel wall, W/(m$^2$ °C); $l_c$ and $l_e$ are the thickness of the concrete wall and the burial depth (Ampofo et al. 2004b), respectively, m; $\lambda_c$ and $\lambda_e$ are the thermal conductivity of concrete wall and tunnel surrounding rock, respectively, W/(m °C).

Model 2 (Wu et al. 2008):

\[
q_2 = \left( T_n - T_0 \right) / \left( \frac{8R_1}{3\alpha} + \frac{1}{\alpha} \right)
\]

(9)

where $q_2$ is the heat absorption of surrounding rock of the Model 2, W/m$^2$; $T_n$ is the tunnel wind temperature, °C; $T_0$ is the original rock temperature, °C; $R_1$, $R_2$ and $R_3$ are equivalent inner diameter, outer diameter and buried depth of tunnel, respectively, m; $\lambda_1$ and $\lambda_2$ are the thermal conductivity of the concrete wall and tunnel surrounding rock, respectively, W/(m °C).

In this work, there is no distinction between concrete wall and tunnel surrounding rock. Instead, the average thermal conductivity was used to deal with the thermal conductivity of the two. The burial depth of 5 m was taken as an example to calculate the heat absorption. For the Model 1, $\Delta T = 6$ °C, $\alpha_1 = \alpha_2 = 10$ W/(m$^2$ °C), $\lambda_c = \lambda_e = \lambda = 1.84$ W/(m °C), $l_c = 0$ m, $l_e = 5$ m and the $q_1 = 2.13$ W/m$^2$, i.e. $6.72 \times 10^4$ kJ/m$^2$ per year. For the Model 2, $T_n = 22$ °C, $T_0 = 16$ °C, $R_1 = R_2 = 3.043$ m (calculated by equal perimeter method), $R_3 = 5$ m, $\lambda_1 = \lambda_2 = 1.84$ W/(m °C) and the $q_2 = 1.33$ W/m$^2$, i.e. $4.19 \times 10^4$ kJ/m$^2$ per year.

Figure 11 represents the calculated results of the annual heat storage of tunnel surrounding rock using different models. This figure indicates that (i) Model 1 and Model 2 are suitable for steady-state heat transfer, but these two models may produce some errors due to non-stationary nature of the heat exchange between the tunnel airflow and the wall surface; (ii) the calculated results of Model 1 are close to ours, even though the differences are significant. The heat storage we calculated was larger at the beginning and then decreased year by year, but the Model 1’s results remained unchanged and should produce considerable error in prediction; (iii) the results of Model 2 are obviously lower than those of our simulations and the Model 1 due to the errors by the semi-empirical parameters. Taken together, our dual periodic heat transfer model with high accuracy can be used to evaluate the heat storage capacity of the surrounding rock of underground tunnel and provide a reference for thermal disaster prevention of subway tunnel.

Table 5 Variations of $r$-value of surrounding rock mass

| Depth (m) | The 1st year | The 2nd year | The 5th year | The 10th year | The 15th year | The 20th year | The 25th year | The 30th year | Average$^*$ |
|----------|--------------|--------------|--------------|---------------|---------------|---------------|---------------|---------------|-------------|
| 3        | 8.74         | 6.48         | 5.92         | 5.54          | 5.26          | 5.02          | 4.95          | 4.93          |             |
| 5        | 4.88         | 3.64         | 3.34         | 3.13          | 3.01          | 2.93          | 2.88          | 2.86          |             |
| 7        | 4.30         | 3.14         | 2.88         | 2.73          | 2.64          | 2.57          | 2.55          | 2.54          |             |
| 11       | 5.55         | 3.28         | 2.88         | 2.66          | 2.56          | 2.48          | 2.45          | 2.44          |             |
| 15       | 6.69         | 3.49         | 2.89         | 2.60          | 2.49          | 2.42          | 2.38          | 2.37          |             |

Table 6 Total heat storage of tunnel surrounding rock

| Depth (m) | $\bar{Q}_0$ (10$^4$ kJ/m$^2$) | The 1st year | The 2nd year | The 5th year | The 10th year | The 15th year | The 20th year | The 25th year | The 30th year | Average$^*$ |
|-----------|--------------------------------|--------------|--------------|--------------|---------------|---------------|---------------|---------------|---------------|-------------|
| 3         | 11.92                          | 8.93         | 8.56         | 8.27         | 8.04          | 7.91          | 7.87          | 7.86          | 8.21          |             |
| 5         | 10.53                          | 7.51         | 7.04         | 6.68         | 6.45          | 6.33          | 6.23          | 6.19          | 6.63          |             |
| 7         | 10.21                          | 6.87         | 6.37         | 6.07         | 5.85          | 5.73          | 5.68          | 5.65          | 6.03          |             |
| 11        | 10.93                          | 6.31         | 5.65         | 5.24         | 5.02          | 4.88          | 4.81          | 4.78          | 5.24          |             |
| 15        | 11.61                          | 6.27         | 5.35         | 4.84         | 4.61          | 4.50          | 4.41          | 4.37          | 4.91          |             |

*Average values are calculated starting from the second year, excluding the first year
In this work, we had proposed a temperature field model of surrounding rock of subway tunnel in combining with dual periodic temperature boundaries to investigate the heat transfer between tunnel wind and tunnel wall. Numerical analysis was performed to calculate the temperature rise and heat storage of surrounding rock, thus providing a theoretical estimate of the thermal hazard of surrounding rock. The main conclusions can be drawn as follows:

i. The superposition effects of the two periodic temperature boundaries were investigated. The results show that the periodic ground temperature fluctuation only affects the tunnel surrounding rock with the shallow burial depth less than 11 m, but it still has an important influence on the temperature distribution of the tunnel overburden when working with the periodic tunnel wind temperature wave together, which makes the temperature of this influenced region higher in autumn.

ii. The pattern of temperature variations of tunnel wall surface was illustrated. The results reveal that the temperatures of the points on the wall surface also fluctuate in the form of simple harmonic waves, and their amplitude and wavelength wave are basically the same as those of the periodic tunnel wind wave, but there are still some differences, mainly in the wall surface temperature waves lagging. It is these temperature differences that provide the driving force for the heat exchange between the surrounding rock and the tunnel wind flow.

iii. The estimation of the temperature rise and heat storage of surrounding rock of subway tunnel was conducted. The results indicate that the total heat storage decreases year after year, but the rate of decrease gradually becomes smaller until it stabilizes. The average heat storage for our specific example reaches about $6.63 \times 10^4$ kJ/m$^2$ per year when buried 5m deep, but this value is related to the burial depth, thermal environment, lithology, tunnel shape, etc. Under the influence of dual periodic temperature boundaries, the shallower the tunnel depth, the higher the temperature rise in the surrounding rock and the greater the thermal hazards.

Acknowledgements We appreciate the Editor’s efforts and the anonymous reviewers who provided valuable comments and suggestions on our research.

Author contribution WL: conceptualization; methodology; writing—review and editing; funding acquisition. SL: formal analysis; validation; writing—original draft preparation. QH: data curation; formal analysis; writing—review and editing; investigation. YQ: project administration; visualization; supervision. All authors read and approved the final manuscript.

Funding This study was supported by the National Natural Science Foundation of China (Grant numbers 52074303, 51874315) and the China Postdoctoral Science Foundation (Grant numbers 2018M630183).

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.
References

Adil Zainal O, Yumruta R (2015) Validation of periodic solution for computing CLTD (cooling load temperature difference) values for building walls and flat roofs. Energy 82:758–768

Alkhaier F, Flerchinger GN, Su Z (2012) Shallow groundwater effect on land surface temperature and surface energy balance under bare soil conditions: modeling and description. Hydrol Earth Syst Sci 16:1817–1831

Ampofo F, Maidment G, Missenden J (2004) Underground railway environment in the UK Part 1: Review of thermal comfort. Appl. Therm. Eng. 24:611–631

Ampofo F, Maidment G, Missenden J (2004) Underground railway environment in the UK Part 2: Investigation of heat load. Appl. Therm. Eng. 24:633–645

Barla M, Di Donna A, Pertino A (2016) Application of energy tunnels to an urban environment. Geothermics 61:104–113

Bogdanovská G, Molnár V, Fedorko G (2019) Failure analysis of condensing units for refrigerators with refrigerant R134a, R404A. Int J Refrig 100:208–219

Dong Z, Qin Y, Wu J, Guo K (2019) Experimental analysis on temperature field variations of heterogeneous surrounding rock under the condition of periodically changing mine ventilation. Energy Sources Part A: Recov Utiliz Environ Effects 43:1869–1879

Feng Q, Jiang BS, Zhang Q, Wang G (2016) Reliability research on the 5-cm-thick insulation layer used in the Yuximoelag tunnel based on a physical model test. Cold Reg. Sci. Tech. 124:54–66

Gow LJ, Barrett DJ, O’Grady AP, Renzullo LJ, Phinn SR (2018) Subsurface water-use strategies and physiological responses of subtropical eucalypt woodland vegetation under changing water-availability conditions. Agricul Forest Meteorol 248:348–360

Hu ZH, Li XZ, Zhao XB, Xiao L, Wu W (2008) Numerical analysis of factors affecting the range of heat transfer in earth surrounding three subways. J China Univ Min Technol 18:67–71

Insana A, Barla M (2020) Experimental and numerical investigations on the energy performance of a thermo-active tunnel. Renew. Energy 152:781–792

Jenkins K, Gilbey M, Hall J, Glenis V, Kilshy C (2014) Implications of climate change for thermal discomfort on underground railways. Transp Res Part D: Transp Environ 30:1–9

Ji YZ, Tu GB, Sun L (2001) Discussion on energy saving method of three subways. J China Univ Min Technol 18:67–71

Jiang B (2018) Research on air temperature of metro tunnel during the initial stage. Urban Rapid Rail Transit 31:113–118

Jin X, Zhang XS, Cao YR, Wang G (2012) Thermal performance evaluation of the wall using heat flux time lag and decrement factor. Energy Build. 47:369–374

Jin H, Yu KW, Gong QM, Zhou SH (2018) Load-carrying capability of shield tunnel damaged by shield shell squeezing action during construction. Thin-Walled Struct. 132:69–78

Jun KJ, Hwang YC, Yune CY (2017) Field measurement of temperature inside tunnel in winter in Gangwon, Korea. Cold Reg. Sci. Tech. 143:32–42

Ke MT, Cheng TC, Wang WP (2002) Numerical simulation for optimizing the design of subway environmental control system. Build. Environ. 37:1139–1152

Krasyk AM, Lugin IV, P’yankova AY (2015) Delineation of soil body area exposed to thermal effect of subway stations and tunnels. J Min Sci 51:138–143

Li YA, Gao YN, Yang ZJ, Liu XL (2011) Study on change regularity of air temperature underground tunnel based on intermittent operating of heat pump. Appl Mech Mater 90–93:1671–1674

Li XZ, Xiong ZY, Qiao HJ, Ma J, Zhang XH, Du J (2012) Monitoring and analysis of heat transfer through surrounding rocks of subway tunnel. Chin J Undergr Space Eng 8:105–110

Li Z, Chen C, Pan S, Yan L, Li K (2015) The effective use of the piston effect, natural cold sources, and energy saving in Beijing subways. Adv Mech Eng 5:371785

Li B, Han ZW, Bai CG, Hu HH (2019) The influence of soil thermal properties on the operation performance on ground source heat pump system. Renew. Energy 141:903–913

Liang B, Zhao NY (2011) A study on temperature distribution of surrounding rock and mechanical characteristics of lining of Monglian tunnel under high geothermal. Int Conf Civil Eng Build Mater (CEBM) CHINA 255–260:2594–2600

Liu W, Qin Y (2017) Multi-physics coupling model of coal spontaneous combustion in longwall gob area based on moving coordinates. Fuel 188:553–566

Mao YHF, Liu HX (1993) The heating value and load calculation for the subway. J Tunn Translat 8:16–25

Ogulnleye O, Singh RM, Cecnato F, Chan Choi J (2020) Effect of intermittent operation on the thermal efficiency of energy tunnels under varying tunnel air temperature. Renew. Energy 146:2646–2658

Qin YP, Jia JY, Liu W, Yang XB (2013) Four finite volume schemes for heat transfer problems. J Liaoning Tech Univ 32:763–767

Qin YP, Song HT, Wu JS, Bai YX, Dong ZY, Ye F (2015) Analysis of surrounding rock heat dissipation for trapezoid roadway by finite-volume method. J Liaoning Tech Univ 34:898–904

Qin YP, Song HT, Wu JS, Dong ZY (2015) Numerical analysis of temperature field of surrounding rock under periodic boundary using finite volume method. J China Coal Soc 40:1541–1549

Revesz A, Chaer I, Thompson J, Mavroulidou M, Gunn M, Maidment G (2016) Ground source heat pumps and their interactions with underground railway tunnels in an urban environment: A review. Appl. Therm. Eng. 93:147–154

Shi CH, Cao CY, Lei MF (2017) An analysis of the ground deformation caused by shield tunnel construction combining an elastic half-space model and stochastic medium theory. KSCE J. Civ. Engr. 21:1933–1944

Slub F, Castaing-Lasvignettes J, Strub M, Pons M, Monchoux F (2005) Second law analysis of periodic heat conduction through a wall. Int. J. Therm. Sci. 44:1154–1160

Sun C, Shu SM, Ding GZ, Zhang XQ, Hu XH (2013) Investigation of time lags and decrement factors for different building outside temperatures. Energy Build. 61:1–7

Tan XJ, Chen WZ, Yang DS, Dai YH, Tian HM, Zhao WS (2014) Study on the influence of airflow on the temperature of the surrounding rock in a cold region tunnel and its application to insulation layer design. Appl. Therm. Eng. 67:320–334

Tong L, Hu ST, Lu S, Wang YM (2019) Study on heat transfer performance of metro tunnel capillary heat exchanger. Sust. Cities Soc. 45:683–685

Tong Z, Cao T, Zang G, Hu S, Liu G, Wang Y (2020) Performance analysis of capillary front-end heat exchanger for subway tunnel. Appl Therm Eng 174:115360

Tong LH (2005) Study on energy saving control of thermal environment of Beijing Metro Line 1 and 2. The 13th National HVAC.
Technical Information Network Technology Exchange Conference, China, pp. 435-440
Transportation USDo (1975) Subway environmental design handbook—V.1—Principles and applications.
Unver B, Agan C (2003) Application of heat transfer analysis for frozen food storage caverns. Tunn. Undergr. Space Technol. 18:7–17
Wang Y, Li XF (2018) STESS: subway thermal environment simulation software. Sust. Cities Soc. 38:98–108
Wang ZM, Zhang W, Lei CZ, Ding PL, Sun K (2014) Numerical prediction of the long-term soil temperature variations around shallow sections of cross-river road tunnels. J Southeast Univ 30:480–488
Wang YC, Feng HR, Xi XY (2017) Monitoring and autonomous control of Beijing Subway HVAC system for energy sustainability. Energy Sustain Dev. 39:1–12
Wu W, Li XZ, Hu ZH, Xiao L (2008) Calculating methods of heat transfer quantity through surrounding rocks in metro design. Chin J Undergr Space Eng 4:89–93
Xiaozhao L, Zhiyong X, Hengjun Q, Juan M, Xuehua Z, Maojin D (2012) Monitoring and analysis of heat transfer through surrounding rocks of subway tunnel. Chin J Undergr Space Eng 8:105–110
Xu TY, Wang MN, Yu L, Lv C, Dong YC, Tian Y (2019) Research on the earth pressure and internal force of a high-fill open-cut tunnel using a bilayer lining design: a field test using an FBG automatic data acquisition system. Sensors. 19:1487–1505
Xu ZG, Du XL, Xu CS, Hao H, Bi KM, Jiang JW (2019) Numerical research on seismic response characteristics of shallow buried rectangular underground structure. Soil Dyn. Earthq. Eng. 116:242–252
Xu ZH (2002) Determination of air conditioning loads and the loads analysis of ice storage system in subway. Refrigeration & Air-condition 01:11–14
Yu WB, Lu Y, Han FL, Liu YZ, Zhang XF (2018) Dynamic process of the thermal regime of a permafrost tunnel on Tibetan Plateau. Tunn. Undergr. Space Technol. 71:159–165
Yuan YP, Gao XK, Wu HW, Zhang ZJ, Cao XL, Sun LL, Yu NY (2017) Coupled cooling method and application of latent heat thermal energy storage combined with pre-cooling of envelope: Method and model development. Energy 119:817–833
Zhang Y, Li XF (2018) Heat transfer formalism using GFM and FEM in underground tunnels. Build Environ 143:717–726
Zhang Y, Li XF (2019) Response-surface-model based on influencing factor analysis of subway tunnel temperature. Build. Environ. 160:106140
Zhang Y, Li X (2020) Monitoring and analysis of subway tunnel thermal environment: a case study in Guangzhou, China. Sust. Cities Soc. 55:102057
Zhang GZ, Xia CC, Sun M, Zou YC, Xiao SG (2013) A new model and analytical solution for the heat conduction of tunnel lining ground heat exchangers. Cold Reg. Sci. Tech. 88:59–66
Zhang H, Zhu CG, Zheng WD, You SJ, Ye TZ, Xue P (2016) Experimental and numerical investigation of braking energy on thermal environment of underground subway station in China’s northern severe cold regions. Energy 116:880–893
Zhang H, Cui T, Liu MZ, Zheng WD, Zhu CG, You SJ, Zhang YZ (2017) Energy performance investigation of an innovative environmental control system in subway station. Build. Environ. 126:68–81

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.