Estimation of Thermal Hazards in Surrounding Rock of Subway Tunnel Under Dual Periodic Temperature Boundaries: A Case Study

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

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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;

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23 **1 Introduction**

24 Subway has become a widely used means of transportation in the world. A long-term operation of
25 the train will generate a lot of heat, resulting in a gradual increase in the temperature of the tunnel
26 surrounding rock and wind flow, and the thermal hazards gradually becomes apparent (Zhang and Li
27 2020). The heat accumulation in the London subway has caused the tunnel temperature to rise from
28 14°C in the early 1900s to over 30°C today (Tong et al. 2019). In Hong Kong, the subway had to
29 cool the tunnel cave with seawater in winter to cope with the inadequate design of environmental
30 control (Ji et al. 2001). For Beijing Metro Line 1, its air temperature in summer had already exceeded
31 28.5°C, and still rose at a rate of 0.2°C per year (Tong 2005). High tunnel temperatures not only
32 cause discomfort to passengers, but also affect the safe operation of the trains (Ampofo et al. 2004a).
33 When the tunnel air temperature is so high that the inlet temperature of the condenser exceeds 45°C,
34 the train's air conditioner will not be able to turn on the power, thus causing operational hazards
35 (Bogdanovská et al. 2019). Therefore, more attention should be paid to the thermal hazards of
36 subway tunnel.

37 Currently, research on thermal hazards control in tunnels has mainly focused on the extraction and
38 utilization of tunnel heat, optimization of ventilation networks, and upgrading of environmental
39 control systems, etc., but the function of tunnel surrounds in regulating the thermal environment of
40 tunnels has rarely been addressed (Insana and Barla 2020; Li et al. 2015; Ogunleye et al. 2020; Tong
41 et al. 2020; Zhang et al. 2017). In fact, the surrounding rock of the tunnel can absorb or release a
42 considerable heat to adjust the temperature of airflow in tunnels (Revesz et al. 2016; Wang et al.
43 2017; Zhang et al. 2017). There have been a number of investigations about the heat transfer of
44 surrounding rocks carried out in the fields of mine thermal disaster, tunnel freezing damage in cold
45 area, underground storage freezer and ground source heat pump (Qin et al. 2015b; Revesz et al. 2016;
46 Unver and Agan 2003; Yu et al. 2018), but rarely involves the subway tunnel. It is crucial to
47 investigate the heat transfer of surrounding rock of subway tunnel for the thermal hazards prevention.

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

66 Numerical calculation is one of major approaches to investigate the thermal disaster of subways.
67 In 1975, the software of subway environment simulation (SES) had been developed by the United
68 States (Transportation 1975), which was applied in designing the subways of Atlanta, New York,
69 Hong Kong, etc., but this software could not get the spatial temperature distribution due to its basis
70 on Bernoulli equation and pipe network theory (Ke et al. 2002). A specialized software system called
71 STESS (Wang and Li 2018) was developed in China since 1979 to simulate the piston wind effect
72 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; Zhang and Li 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). Krasnyuk 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 (Krasnyuk 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.

2 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 this 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).

98 There are some assumptions need to be clarified: (i) the tunnel surrounding rock is homogeneous
 99 and isotropic with no internal heat source, and its thermal conductivity uses the average value of the
 100 thermal conductivity of all rock layers; (ii) the temperature difference and heat flux along the tunnel
 101 axis are neglected; (iii) the effect of train running on the heat exchange of tunnel wall is not
 102 considered in modeling; (iv) the initial temperature of the surrounding rock is set as the temperature
 103 of the soil thermostat layer that is close to the annual average temperature of the ground (Jin et al.
 104 2012; Sun et al. 2013; Zhang and Li 2018). In this way, the temperature field of the tunnel
 105 surrounding rock can be simplified into a two-dimensional unsteady model.

106 *2.1 Governing equation of heat transfer of surrounding rock*

107 The change of temperature field of tunnel surrounding rock belongs to the category of physical
 108 thermal conduction, and its integral equation expresses as

$$109 \quad -\oint_l \frac{\partial T}{\partial n} dl = \iint_S \rho c \frac{\partial T}{\partial t} dS \quad (1)$$

110 where T is the temperature of surrounding rock, °C; $\mathbf{n}$ is the outward normal direction of the
 111 boundary; λ is the thermal conductivity of surrounding rock, W/(m·°C); ρ is the density of
 112 surrounding rock, kg/m³; c is the specific heat capacity of surrounding rock, J/(kg·°C); t is time, s; l
 113 is the boundary of the integration region, m; S is the area of the integration region, m².

114 *2.2 Dual periodic temperature boundaries*

115 Fig. 1 shows a cross section of surrounding rock of a rectangular tunnel. It can be found that there
 116 are three boundaries for the above model: ground-level boundary, tunnel wall boundary, and the deep
 117 boundary of surrounding rock, which are named Γ_1 , Γ_2 , and Γ_3 , respectively. Fig. 2 further illustrates
 118 the ground-level atmospheric temperature variation in Suzhou City referring to the weather data of
 119 the past three years from the National Meteorological Center of China. This indicates that the annual
 120 variation of the ground atmospheric temperature can be viewed as a complete simple harmonic. The
 121 airflow in the tunnel from the ground atmosphere should correspondingly change in another simple

122 harmonic form (Adil Zainal and Yumruta 2015; Jun et al. 2017; Strub et al. 2005; Wang et al. 2014).

123 Their sinusoidal equations are expressed as:

$$\begin{cases} T_{f_1} = \overline{T}_{f_1} + A_{f_1} \sin(2\pi t / \tau + \varphi_1) \\ T_{f_2} = \overline{T}_{f_2} + A_{f_2} \sin(2\pi t / \tau + \varphi_2) \end{cases} \quad (2)$$

125 where T_{f1} and T_{f2} represent the ground-level temperature and the tunnel air temperature,
 126 respectively, °C; $\overline{T}_{f1}$ and $\overline{T}_{f2}$ are the average values of the sine waves, respectively, °C; A_{f1} and A_{f2}
 127 are the amplitudes of the ground-level temperature and tunnel air temperature, respectively, °C; τ is
 128 the annual period, s; φ_1 and φ_2 are phase angles.

Fig. 1 Schematic diagram of surrounding rock of a rectangular tunnel

Fig. 2 Atmospheric temperature in Suzhou City from the National Meteorological Center of China

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

$$\begin{cases} -\lambda \frac{\partial T}{\partial n} \Big|_{\Gamma_1} = \alpha_1 (T_{\Gamma_1} - T_{f1}) \\ -\lambda \frac{\partial T}{\partial n} \Big|_{\Gamma_2} = \alpha_2 (T_{\Gamma_2} - T_{f2}) \\ T \Big|_{\Gamma_3} = T_0 \end{cases} \quad (3)$$

where α_1 and α_2 are the convection heat transfer coefficients of boundary Γ_1 and Γ_2 , respectively, $W/(m^2 \cdot ^\circ C)$; T_{Γ_1} and T_{Γ_2} are the temperatures of ground boundary and the tunnel wall boundary, respectively, $^\circ C$; T_0 is the original rock temperature, $^\circ C$.

Eq. (1) and Eq. (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.

3 Simulation calculations

3.1 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

154 of Suzhou City used the atmospheric data shown in Fig.1, but the solar radiation was ignored. The
 155 tunnel air temperature cited the on-site data in Re. (Jiang 2018) that had measured the air temperature
 156 variation in the tunnel of the Suzhou Metro Line 2. It is assumed that the phase angles of the ground
 157 atmospheric temperature wave and the tunnel wind temperature wave are both zero at the first
 158 iteration. The periodic variations of the air temperature in tunnel and near the ground were
 159 determined as follows:

$$160 \quad \begin{cases} T_{f_1} = 16 + 21 \sin(2\pi t / \tau) \\ T_{f_2} = 22 + 5.5 \sin(2\pi t / \tau) \end{cases} \quad (4)$$

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

166 Table 1 Thermophysical properties of surrounding rock of subway

	Symbol	Value	Unit
Average thermal conductivity	λ	1.84	W/(m·°C)
Average density	ρ	2250	kg/m ³
Average specific heat capacity	c	0.84	J/(kg·°C)
Convection heat transfer coefficient of ground	α_1	5	W/(m ² ·°C)
Convection heat transfer coefficient of tunnel	α_2	10	W/(m ² ·°C)
Original rock temperature	T_0	16	°C

167 3.2 Grid division and solving

168 A suitable meshing is the premise for calculating the temperature field of surrounding rock. Due to
 169 a strong adaptability to the irregular calculative region around the tunnel as shown in Fig. 1, the
 170 triangular cell was used to solve the mesh division. Considering that the temperature variations close
 171 to the tunnel wall and the ground were drastic, the closer to these two areas, the finer the mesh, but

172 the deeper into the surrounding rock, the rougher the mesh, shown in Fig. 3. The physical model was
 173 divided into 1684 nodes and 3200 cells. Such a gradually expanding meshing greatly improved the
 174 accuracy and speed of the calculations. Based on the triangular mesh, the temperature field model
 175 was discretized by the Finite Volume Method (Liu and Qin 2017), and we developed independently a
 176 solver to calculate this discrete model. The iteration time was incremented at equal intervals, and the
 177 step time was calculated by 1/10000 of the annual period. The temperature of all nodes calculated at
 178 the previous moment was used as the initial condition for calculating the temperature of the nodes at
 179 the next moment. Finally, the temperature data of all nodes were output at the set time.

180
 181 Fig. 3 Schematic diagram of grid division of tunnel section

182 **4 Results and analysis**

183 *4.1 Temperature variation of surrounding rock section*

184 Fig. 4 represents the comparison results of temperature distribution of tunnel surrounding rock
 185 among the 2nd, the 5th and the 10th year after ventilation when the buried depth of tunnel roof is 5 m.
 186 Four equidistant moments in one annual cycle, i.e. $t = k\tau/4$ ($k = 1, 2, \dots, N$; τ is the annual cycle; the
 187 abscissa between 0 and 1 is defined as the first year), are selected to intuitively display the
 188 temperature distribution in the typical days of the four seasons. In this figure, we can find that the
 189 periodic ground-level temperature wave has a limited effect on the underground depth, about -11m,

190 and this effect depth has not increased much even after 10 years, while the influence range of the
191 periodic tunnel wind temperature wave on the surrounding rock mass is larger and larger over time.
192 There are some regions affected by the duplicate effects of these two periodic temperature waves,
193 such as the region above the roof of the tunnel. The effects are most prominent in autumn, resulting
194 in a higher temperature in this region. In fact, the temperature wave can transmit from the ground
195 into the surrounding rock mass below. When encountering the temperature wave of the tunnel wind,
196 these two waves are superposed on each other and affect the temperature distribution around the
197 tunnel. Predictably, the shallower the tunnel is buried, the stronger these effects will be.

Fig. 4 Temperature field distributions of tunnel surrounding rock when buried 5m deep

4.2 Temperature variation of tunnel wall surface

Fig. 5 illustrates that 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. 9 (a), 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. 9(b) 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.

Fig. 5 Temperature variations of three monitoring points on tunnel wall surface over time

223 4.3 Temperature waves in the surrounding rock mass

224 Fig. 6 manifests the variations of temperature waves in the surrounding rock mass at different
225 depths above and below the tunnel, where the monitoring point 1 was set at the ground, the point 2 at
226 2.5m deep, and the point 3 was arranged at 17m deep, shown in Fig. 1. It can be seen that the
227 temperature waves have hysteresis at various layers between the ground and the tunnel wall. The
228 further away from the ground or the tunnel wall, the greater the temperature wave lag and the faster
229 the wave amplitude decays. The temperature amplitude of monitoring point 2 is only 3/4 of the point
230 1's, while the amplitude of point 3 tends to zero due to its deep burial. In addition, the temperature of
231 surrounding rock below the tunnel floor is increasing year by year. The point 3' temperature has
232 increased by 2.6 °C within ten years.

233 Fig. 7 exhibits the temperature variations on the vertical axis of symmetry of tunnel surrounding
234 rock section at the 9th year. In this figure, the amplitude of temperatures wave gradually decrease as
235 the depth of rock stratum increases. When the depth exceeds 17m, the fluctuations of temperature are
236 no longer significant, and all tend to be the original rock temperature. It indicates that the
237 surrounding rock mass much deeper than the tunnel floor is basically unaffected by the dual periodic
238 temperature waves, but the rock temperature around the tunnel fluctuates greatly.

239

240

Fig. 6 Variations of temperature waves in the surrounding rock mass at different depths

242

243 Fig. 7 Temperature variations on the vertical axis of symmetry of tunnel surrounding rock section the 9th year

244 **5 Estimation of thermal hazards**

245 *5.1 Estimates of temperature increase in the surrounding rock*

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

Fig. 8 Temperature distribution on the vertical symmetry axis of the tunnel surrounding rock section in summer (a.

Buried depth 5 m; b. Buried depth 11 m)

259 Table 2 Average temperature rise of surrounding rock under different buried depth

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

260 5.2 Heat Flow of tunnel wall

261 In this work, the mesh of the tunnel wall had been appropriately densified to improve the
 262 calculation accuracy. The rectangular tunnel wall was divided into N elements, and the temperature
 263 of each node was expressed in terms of $T_1, T_2, T_3, \dots T_N$, in which the length between two adjacent
 264 nodes was marked in terms of $L_1, L_2, L_3, \dots L_n$, and the total length was L . The average value method
 265 was used to calculate the average temperature of the tunnel wall, which was related to the calculation
 266 of heat transfer quantity of surrounding rock, as follows:

$$267 \quad T_w = \frac{\sum_{i=1}^{n-1} \frac{T_i + T_{i+1}}{2} L_i + \frac{T_n + T_1}{2} L_n}{L} \quad (5)$$

268 where T_w is the average temperature of the tunnel wall, °C.

269 The heat flux on the tunnel wall should be imported or exported periodically under the dual
 270 periodic variation boundaries. According to Fourier's law, the heat flux on the tunnel wall can be
 271 expressed as:

$$272 \quad \begin{cases} q_+ = \alpha(T_f - T_w) & T_f > T_w \\ q_- = \alpha(T_f - T_w) & T_f < T_w \end{cases} \quad (6)$$

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

275 Fig. 9 reveals the variations of wind temperature, average wall surface temperature and heat flux

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

290
 291 Fig. 9 Variations of wind temperature, average wall surface temperature and heat flux when buried 5m deep

292 Table 3 Time differences of η and ε under different buried depth

Time differences	Time (Day)						
	3m	5m	7m	9m	11m	13m	15m
η	5.66	5.66	4.75	3.76	3.29	3.20	3.18
ε	82.19	55.99	41.25	33.77	31.22	31.21	31.18

293 *5.3 Heat transfer quantity of surrounding rock*

294 The heat transfer on tunnel wall surface can be calculated through integrating heat flux with time.

295 The heat absorption quantity per unit area ($\bar{Q}_+$, kJ/m²) and heat dissipation quantity per unit area

296 ($\bar{Q}_-$, kJ/m²) of the tunnel surrounding rock in the N^{th} year can be obtained as

$$\begin{cases} \bar{Q}_+ = \int_{t_1}^{t_2} \alpha_2 (T_{f_2} - T_w) dt \\ \bar{Q}_- = \int_{t_2}^{t_3} \alpha_2 (T_{f_2} - T_w) dt \end{cases} \quad (7)$$

298 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
299 cooling interval, s.

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

307 Table 4 (a) Heat absorption quantity of surrounding rock mass

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

308 Table 4 (b) Heat dissipation quantity of surrounding rock mass

Depth (m)	$\bar{Q}_- (10^4 \text{ kJ/m}^2)$							
	the 1st	the 2nd	the 5th	the 10th	the 15th	the 20th	the 25th	the 30th
	year	year	year	year	year	year	year	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	-2.52	-2.83	-3.02	-3.09	-3.16	-3.19	-3.20

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

Depth (m)	$r (\%)$							
	the 1st	the 2nd	the 5th	the 10th	the 15th	the 20th	the 25th	the 30th
	year	year	year	year	year	year	year	year
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	5.35	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

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

312 Table 6 Total heat storage of tunnel surrounding rock

Depth (m)	$\bar{Q}_0 (10^4 \text{ kJ/m}^2)$								
	the 1st	the 2nd	the 5th	the 10th	the 15th	the 20th	the 25th	the 30th	Average*
	year	year	year	year	year	year	year	year	
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

313 * Average values are calculated starting from the second year, excluding the first year.

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

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

Fig. 10 Total heat storage capacity of the surrounding rock under dual periodic temperature boundaries

5.4 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):

$$q_1 = \frac{\Delta T}{\frac{1}{\alpha} + \frac{l_c}{\lambda_c} + \frac{l_e}{\lambda_e}} \quad (8)$$

where q_1 is the heat absorption of surrounding rock of the Model 1, W/m²; ΔT is the temperature difference between tunnel wind flow and the original rock temperature, °C; α is the convection heat transfer coefficient of tunnel wall, W/(m²·°C); l_c and l_e are the thickness of the concrete wall and the burial depth (Ampofo et al. 2004b), respectively, m; λ_c and λ_e are the thermal conductivity of concrete wall and tunnel surrounding rock, respectively, W/(m·°C).

Model 2 (Wu et al. 2008):

$$\begin{cases} q_2 = (T_n - T_0) / (\frac{8R_1}{3\lambda} + \frac{1}{\alpha}) \\ \lambda = \frac{\ln R_3 - \ln R_1}{\frac{\ln R_2 - \ln R_1}{\lambda_1} + \frac{\ln R_3 - \ln R_2}{\lambda_2}} \end{cases} \quad (9)$$

where q_2 is the heat absorption of surrounding rock of the Model 2, W/m²; 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; λ_1 and λ_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, $\Delta T = 6^\circ\text{C}$, $\alpha = \alpha_2 = 10 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$, $\lambda_c = \lambda_e = \lambda = 1.84 \text{ W}/(\text{m} \cdot ^\circ\text{C})$, $l_c = 0 \text{ m}$, $l_e = 5 \text{ m}$, and the $q_1 = 2.13 \text{ W}/\text{m}^2$, i.e. $6.72 \times 10^4 \text{ kJ}/\text{m}^2$ per year. For the Model 2, $T_n = 22^\circ\text{C}$, $R_1 = R_2 = 3.043 \text{ m}$ (calculated by equal perimeter method), $R_3 = 5 \text{ m}$, $\lambda_1 = \lambda_2 = \lambda = 1.84 \text{ W}/(\text{m} \cdot ^\circ\text{C})$, and the $q_2 = 1.33 \text{ W}/\text{m}^2$, i.e. $4.19 \times 10^4 \text{ kJ}/\text{m}^2$ per year.

Fig. 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.

Fig. 11 Calculated results of the annual heat storage of tunnel surrounding rock using different models

6 Conclusion

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 were illustrated. The results reveal that the temperatures of the points on the wall surface also fluctuates 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 6.63×10^4 kJ/m² 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.

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Figures

Figure 1

Schematic diagram of surrounding rock of a rectangular tunnel

Figure 2

Atmospheric temperature in Suzhou City from the National Meteorological Center of China

Figure 3

Schematic diagram of grid division of tunnel section

Figure 4

Temperature field distributions of tunnel surrounding rock when buried 5m deep

Figure 5

Temperature variations of three monitoring points on tunnel wall surface over time

Figure 6

Variations of temperature waves in the surrounding rock mass at different depths

Figure 7

Temperature variations on the vertical axis of symmetry of tunnel surrounding rock section the 9th year

Figure 8

Temperature distribution on the vertical symmetry axis of the tunnel surrounding rock section in summer
(a. Buried depth 5 m; b. Buried depth 11 m)

Figure 9

Variations of wind temperature, average wall surface temperature and heat flux when buried 5m deep

Figure 10

Total heat storage capacity of the surrounding rock under dual periodic temperature boundaries

Figure 11

Calculated results of the annual heat storage of tunnel surrounding rock using different models