Study on Dust Concentration Control Index during Construction of High Altitude Tunnel

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Abstract: In view of the high altitude tunnel construction dust serious threat to the health of the construction workers. By investigating the characteristics of high-altitude climate, the influence of climate at different altitudes on blood oxygen saturation and human respiration was analyzed, and the dust concentration control index during the construction period of high-altitude drilling-blasting tunnel was studied. The results show that with the elevation increasing, the dust concentration index correction coefficient decreases and the dust concentration control index decreases. This is due to the gradual decrease of atmospheric pressure, the decrease of oxygen content and partial pressure of oxygen in the air, leading to the decrease of human blood oxygen saturation, the acceleration of human respiratory frequency, and the increase of dust inhalation per unit time. Therefore, it is necessary to reduce the concentration of dust in the construction environment to control the amount of dust inhaled by the human body, so as to ensure the health of the construction personnel.

1. Introduction

With advancing tunneling technology in China, increasing highway tunnels are being built in the western region of China, especially in high altitude areas with inadequate transport infrastructure including Qinghai and Tibet. High altitude areas feature low atmospheric pressure, low air temperature, low content of oxygen in the air, dry air, strong wind and large difference in temperature between day and night. These special environmental conditions have severe impacts on ventilation effectiveness in the tunnel during construction, resulting in large amounts of suspended dust in tunnel air and posing a serious threat to the physical health of tunnel workers. Consequently, there is an urgent need to study dust control technique during construction of high altitude tunnels.

Dust pollution poses a serious hazard to construction safety and workers' health. Long-term inhalation of dust containing free silicon dioxide in certain concentration, in particular, would cause pneumoconiosis, a systemic disease characterized by diffuse fibrosis in lung tissues. In view of the threat posed by toxic gas and dust generation during tunneling to workers' health, Tan Xinrong et al. [1-4] proposed a combination of ventilation measures involving dry dust collector, forced ventilation and gallery ventilation to effectively reduce dust content and ensure in-tunnel air quality. To address the adverse effect of dust produced during TBM tunneling on construction safety, Hu Yi [5] and Guo Chun [6] et al. performed numerical simulation and on-site testing of dust movement pattern and distribution during tunneling. Given the high concentration of dust during construction of highway

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tunnels by drill-and-blast (D&B) method, Sun Zhongqiang [7], Ge Wenchang [8] et al. investigated dust generation mechanism and movement pattern in D&B tunnels.

In a low-oxygen, low-pressure environment at high altitudes people tend to suffer anoxia, chest distress, dizziness and tachycardia as their physiological functions drop to 60% of those at low altitude areas in the short term; they would suffer arrhythmia, irregular heartbeat and other chronic high altitude sicknesses in the long term. Excessive dust concentration in the air would decrease oxygen content further and induce altitude stress, undermining function of human body. Wang Wenming et al. [9] studied the impact of altitude on the lung function of workers operating in a dusty environment and concluded that such workers' lung function decreases markedly with increasing altitude, especially for workers in a high-altitude dusty environment. Wan Zhuying et al. [10] investigated blood pressure of workers operating in a high-altitude (3400m) dusty environment and concluded the hypertension detection rate among such workers is up to 25.6%. Zhao Ping [11] discussed the impact of dust on workers' blood lipid level in high altitude areas and concluded their blood lipid levels increase with working years and that blood lipid levels of workers with many working years are significantly higher than those with a few working years. Therefore, in view of the difference in dust concentration in the air between high and low altitude areas, study of dust control index during construction of highway tunnels is important to effective control of dust concentration during construction of high altitude tunnels and safeguarding workers' physical health.

By investigating the characteristics of high-altitude climate, this paper proposes to analyze the impact of different altitudes on blood oxygen saturation and human respiratory rate and study dust control index during construction of D&B tunnels.

2. Impact of High-altitude Climate on the Function of Human Body

2.1. Analysis of high-altitude climate

Compared with low altitude areas, high altitude ones are characterized by low oxygen content in the air, low atmospheric pressure and coldness, as detailed below:

In high altitude areas, oxygen concentration in the air drops with atmospheric pressure, but the percent (by volume) of oxygen in the air will not change with altitude. Therefore, oxygen concentrations in areas at different altitudes can be calculated using equivalent oxygen concentration. According to its definition, the equivalent oxygen concentration can be calculated from:

\[ C = \frac{C_h (p_0 \rho_H - K \rho_0)}{(p_0 - K) \rho_0} \]  

(1)

where \( C \) — equivalent oxygen concentration at standard atmospheric pressure in %; \( C_h \) — oxygen concentration in high altitude areas in %; \( \rho_H \) — air density in high altitude areas in kg/m\(^3\); \( p_0 \) — standard atmospheric pressure in kPa; \( \rho_0 \) — air density at standard atmospheric pressure in kg/m\(^3\); \( K \) — the pressure at which air is saturated with water vapor at 37°C in kPa, typically taken as 6.27. \( \rho_H \) may be calculated by:

\[ \rho_H = \frac{p_H \rho_0}{p_0} \]  

(2)

where \( p_H \) — atmospheric pressure in high altitude areas in Pa.

\[ p_H = p_0 \exp\left(-\frac{MgH}{RT}\right) \]  

(3)

where \( p_0 \) is standard atmospheric pressure in kPa; \( H \) is altitude in m; \( M \) is molar mass of air in g/mol; \( R \) is gas constant in J/(mol.K); \( T \) is absolute air temperature in K; \( g \) is gravitational acceleration in m/s\(^2\).
According to Eq. (1) the equivalent oxygen concentration is mainly influenced by oxygen concentration and air density in high altitude areas. The oxygen concentration in high altitude areas can be obtained from field monitoring. The air density is calculated from Eq. (2). Thus the variation trend of equivalent oxygen concentration and atmospheric pressure with altitude can be obtained.

From the above figure, it is observed that the equivalent oxygen concentration gradually drops with increasing altitude. Due to sharp decrease of oxygen content in high altitude areas and lower oxygen supply and rate of absorption, human body experiences adverse physiological reaction, leading even to death.

2.2. Change in blood oxygen saturation

Blood oxygen saturation ($SpO_2$) is the percentage of oxygen-saturated hemoglobin relative to total hemoglobin (unsaturated + saturated) in the blood. It is calculated from:

$$SpO_2 = \frac{HbO_2}{Hb + HbO_2} \times 100\%$$

Blood oxygen saturation is the most direct parameter reflecting oxygen absorption by human body and an important indicator of human body anoxia levels. It is mainly influenced by labor intensity and change of heart rate. Normal arterial blood oxygen saturation levels in humans are 97 percent. The decrease in partial pressure of oxygen due to altitude increase and sharp decrease in absolute oxygen content in air lead to a drop in oxygen entering the blood in the lung and to lower blood oxygen saturation and partial pressure of blood oxygen. When blood oxygen saturation drops to the lower limit, insufficient oxygen supply to organs will compromise their functions and lead to hypoxia symptoms such as headache, chest tightness, palpitation, vomiting, insomnia, and loss of appetite.

(1) Relationship between labor intensity and blood oxygen saturation

The blood oxygen saturation of human body varies with labor intensity. By fitting blood oxygen saturation and altitude variation under various labor intensities, the change pattern of blood oxygen saturation under different labor intensities can be derived, as shown in Fig. 1. According to this figure there is a negative correlation between labor intensity and blood oxygen saturation at the same altitude: blood oxygen saturation tends to drop with increasing labor intensity.

| Altitude (m) | Blood oxygen saturation (%) | Altitude (m) | Blood oxygen saturation (%) |
|------------|-----------------------------|------------|-----------------------------|
| 1560       | 96.44                       | 450        | 97.89                       |
| 2800       | 93.74                       | 2260       | 94.13                       |
| 3480       | 91.51                       | 3000       | 92                          |
| 4180       | 87.45                       | 3450       | 90.4                        |
| 5050       | 79.2                        | 4100       | 86.44                       |
(2) Relationship between heart rate and blood oxygen saturation

Heart rate is the speed of the heartbeat measured by the number of poundings of the heart per unit of time — typically beats per minute (bpm). The normal resting adult human heart rate in low altitude areas ranges from 60–80 bpm. However, human cardiovascular system reacts noticeably in high altitude areas. Research shows if the heart rate remains at 140~150 bpm for a prolonged time, human body will suffer palpitation and chest distress, heart failure, pulmonary edema and even blackout or shock.

There is a positive correlation between altitude and heart rate rise. If heart rate rises, the corresponding labor intensity shall be decreased so as to ensure workers’ health, i.e. labor intensity in a negative correlation with altitude. To protect high altitude workers’ physical health the corresponding allowable labor intensity shall be gradually decreased.

To sum up, rising heart rate due to human body movement at different altitudes leads to more oxygen consumption and lower blood oxygen saturation; the level of blood oxygen saturation of a resting human at high altitudes is equal to that of a human doing physical labor at low altitudes; blood oxygen saturation drops sharply with increasing labor intensity.

2.3. Change in human respiratory rate

Higher altitudes not only reduce atmospheric pressure and oxygen content in tunneling environment and increase heart rate, but also significantly reduce blood oxygen saturation levels and labor intensity, adversely affecting workers' physical health. Human body requires a constant amount of oxygen per unit of time under identical labor intensity. Because the amount of oxygen inhaled at a time is reduced due to lower oxygen content in the air at higher altitudes, human body needs higher respiratory rate to meet the demand of the function of human body. Therefore, assuming human body needs the same amount of oxygen in high and low altitude areas, the following relationship exists:

\[
C_{o_2} \cdot V_H \cdot \rho_{o_2} \cdot SpO_2 = C_{o_2}' \cdot V_p \cdot \rho_{o_2}' \cdot SpO_2'
\]

where \(C_{o_2}\) is the percent of oxygen by volume in high altitude areas in %; \(V_H\) is the volume of air inhaled in high altitude areas in L/min; \(\rho_{o_2}\) is oxygen density in high altitude areas in g/L; \(SpO_2\) is blood oxygen saturation in %; \(C_{o_2}'\) is percent of oxygen by volume at standard atmospheric pressure in %; \(V_p\) is volume of air inhaled at standard atmospheric pressure in L/min; \(\rho_{o_2}'\) is oxygen density at standard atmospheric pressure, taken as 1.429 g/L; \(SpO_2'\) is blood oxygen saturation at standard atmospheric pressure taken as 98%. The oxygen as a percentage by volume of air can be ignored since it
varies little with altitude. Therefore, $C_{O_2}$ and $C_{O_2}'$ are both taken as 20.9% in calculation. See Table 2 for specific calculation parameters.

| Altitude (m) | Atmospheric pressure (kPa) | Air density (g/L) | Oxygen density $\rho_{O_2}$ (g/L) | Oxygen percentage by volume $C_{O_2}$ (%) | Blood oxygen saturation $SpO_2$ (%) |
|--------------|----------------------------|-------------------|-----------------------------------|------------------------------------------|-----------------------------------|
| 0            | 101.325                    | 1.293             | 1.429                             | 20.9                                     | 98.00                             |
| 1000         | 89.859                     | 1.116             | 1.261                             | 20.9                                     | 97.58                             |
| 2000         | 79.593                     | 1.007             | 1.113                             | 20.9                                     | 95.94                             |
| 3000         | 70.128                     | 0.909             | 0.983                             | 20.9                                     | 92.54                             |
| 4000         | 61.728                     | 0.819             | 0.868                             | 20.9                                     | 87.38                             |
| 5000         | 54.128                     | 0.736             | 0.772                             | 20.9                                     | 80.45                             |

From the calculation result it is known that human respiratory rate increases with altitude and tends to increase faster at higher altitudes. Lower air density and lower equivalent oxygen concentration in the air in high altitude areas lead to higher human respiratory rate and higher heart rate.

3. Study on Dust Concentration Control Index

Metamorphic rock in high altitude areas is widely distributed and of complex types including slate-phylite-mica schist, metasandstone-mica quartz schist-quartzite, metabasite-greenschist-amphibolite, shallow particle rock-granulite and gneiss. The content of silicon dioxide in various rocks is given in Table 3. From this table it is known that the content of SiO$_2$ in tunnel muck is above 30%. Technical Specifications for Construction of Highway Tunnel (JTGF60-2009) specifies allowable concentration of dust in the workplace, as shown in Table 4.

| Lithology | Sandstone | Slate | Shale | Micaschist | Quartzite | Amphibolite | Gneiss |
|-----------|-----------|-------|-------|------------|-----------|-------------|--------|
| Content of SiO$_2$ | 10–20      | 50–60 | 45–80 | 55%–78%       | Above 95   | 30–50       | 50–70  |

| Dust type | Talc dust (mg/m$^3$) | Gypsum dust (mg/m$^3$) | Cement dust (mg/m$^3$) | Silica dust (mg/m$^3$) | Mica dust (mg/m$^3$) | Welding fume (mg/m$^3$) | Other dusts (mg/m$^3$) |
|-----------|---------------------|------------------------|------------------------|------------------------|----------------------|------------------------|------------------------|
|           | Total dust | Respirable dust | Total dust | Respirable dust | Total dust | Respirable dust | Total dust | Respirable dust | Total dust | Respirable dust | Total dust | Respirable dust | Total dust | Respirable dust | Total dust | Respirable dust | Total dust | Respirable dust |
| TWA (mg/m$^3$) | 3        | 1              | 8              | 4                  | 1.5                | 1                    | 0.7            | 2              | 1.5              | 4              | 8              |
| STEL (mg/m$^3$) | 4        | 2              | 10             | 8                  | 6                  | 2                    | 2              | 4              | 3                | 6              | 10             |
Note: TWA—time weighted average workplace exposure to any hazardous contaminant or agent using the baseline of an 8 hour per day work schedule; STEL—Short term exposure limit to a toxic or an irritant substance over 15 minutes.

The allowable workplace exposure limit to dust denotes the acceptable exposure limit to dust at normal respiratory rate. However, at higher respiratory rate, the amount of dust particles inhaled per unit of time rises by several folds. The allowable exposure limit to dust shall be lowered accordingly. As a result, STEL under high altitude conditions needs to be corrected by coefficient k as follows:

\[
\left\{ \begin{array}{l}
C_{H} = kC_p \\
C_{H}V_{H} = C_pV_p
\end{array} \right. \tag{7}
\]

\[
k = \frac{V_p}{V_H} \tag{8}
\]

where \(C_H\) is dust concentration correction index for high altitude areas in mg/m³; \(C_p\) is dust concentration criterion for plain areas in mg/m³; \(V_H\) is respiratory rate in high altitude areas in breath; \(V_p\) is respiratory rate in plain areas in breath.

According to the amplitude of variation in respiratory rate with altitude in Fig. 2, the values of \(k\) at different altitudes are calculated using Eq. (6) and (8), as shown in Fig. 3. By placing the values of \(k\) into Eq. (7) the dust concentration correction index for different altitudes can be obtained, as shown in Table 5.

| Altitude (m) | Talc dust (mg/m³) | Gypsum dust (mg/m³) | Cement dust (mg/m³) | Silica dust (mg/m³) | Mica dust (mg/m³) | Welding fume (mg/m³) | Other dusts (mg/m³) |
|--------------|-------------------|---------------------|---------------------|---------------------|-------------------|----------------------|---------------------|
| Total dust   | 4                 | 3.52                | 2                   | 2                   | 1                 | 4                    | 6                   |
| Respirable dust | 2                 | 1.76                | 10                  | 8                   | 6                 | 2                    | 4                   |
| Total dust   | 8                 | 7.03                | 10                  | 8                   | 6                 | 2                    | 4                   |
| Respirable dust | 2                 | 1.76                | 1.57                | 1.76                | 1.76              | 1.63                 | 1.33                |
| Total dust   | 6                 | 3.52                | 2.64                | 2.64                | 2.64              | 2.64                 | 2.64                |
| Respirable dust | 3                 | 1.76                | 2.64                | 2.64                | 2.64              | 2.64                 | 2.64                |

From Fig. 3 it can be observed that the dust concentration index correction coefficient is variable since the respiratory rate rises by different values at different altitudes. The dust concentration index correction coefficient decreases with increasing altitudes. This suggests the dust control requirements
will become more stringent during tunneling as altitudes increase. At constant dust concentration in the air, a higher respiratory rate due to rising altitude leads to more breaths of dust per unit time and thus more amount of dust being inhaled during a given period of time. Consequently, the dust concentration index shall be lowered, and the index applicable to high altitude areas obtained based on dust concentration index correction coefficient. Table 5 gives main dust correction indices during construction of D&B tunnels calculated using the dust concentration index correction coefficient. The dust concentration control index shall be determined based on the altitude of tunnel site area and climatic conditions during tunneling. Additionally, effective dust removal measures shall be taken to control dust concentrations in the workplace and protect workers' physical health.

4. Conclusions
By investigating the characteristics of high-altitude climate, this paper has analyzed the impact of different altitudes on blood oxygen saturation and human respiratory rate and studied dust control index during construction of D&B tunnels, leading to the following conclusions.

(1) Rising heart rate due to human body movement at different altitudes leads to more oxygen consumption and lower blood oxygen saturation; the level of blood oxygen saturation of a resting human at high altitudes is equal to that of a human doing physical labor at low altitudes; blood oxygen saturation drops sharply with increasing labor intensity.

(2) Human respiratory rate increases with altitude and tends to increase faster at higher altitudes. Lower air density and lower equivalent oxygen concentration in the air in high altitude areas lead to higher human respiratory rate and higher heart rate.

(3) As the elevation increases, the dust concentration index correction coefficient decreases and the dust concentration control index decreases. This is due to the gradual decrease of atmospheric pressure, the decrease of oxygen content and partial pressure of oxygen in the air, leading to the decrease of human blood oxygen saturation, the acceleration of human respiratory frequency, and the increase of dust inhalation per unit time. Therefore, it is necessary to reduce the concentration of dust in the construction environment to control the amount of dust inhaled by the human body, so as to ensure the health of the construction personnel.

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