Influencing factors and treatment measures of wet sliding in tunnel

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Abstract. In order to study the main influencing factors of wet sliding in the tunnel, a regional meteorological observation network was established based on Baojiashan tunnel. Based on the detailed monitoring data for two consecutive years, the influence of air relative humidity, air temperature, temperature difference inside and outside the tunnel, rainfall, wind speed, air pressure in the tunnel and other influencing factors on the tunnel wet sliding phenomenon were analyzed. The results show that the wet-slip phenomenon in the tunnel has no obvious relationship with the rainfall and air pressure changes. It is mainly related to the meteorological conditions of high temperature and humidity outside the tunnel and the wind speed of tunnel ventilation. Based on the analysis of the physical mechanism of tunnel wet sliding phenomenon, a warning table for tunnel wet slip phenomenon was developed in order to promptly warn the tunnel wet slip phenomenon and take countermeasures.

1. Introduction
With the vigorous development of tunnel construction, the construction of highway tunnel is no longer a difficult problem in technology, but some tunnels, especially super long tunnels, appear wet sliding phenomenon in the later operation process, which gradually attracted the attention of engineering and technical personnel. The slippery road will reduce the skid resistance and operation efficiency of the road surface. Once the traffic accidents such as rear end collision are caused, it will also bring adverse social impact [1-4].

Zhu Xufei [5] et al. analyzed the formation mechanism of the wet road surface of the tunnel by observing the geology in Baojiashan tunnel area and the temperature and humidity inside and outside the cave. Jiang Hong [6], etc. took the cement concrete pavement of the long tunnel as the research object, analyzed the influencing factors of the tunnel pavement temperature, and summarized the changing law of the tunnel temperature under each influencing factor. Zheng Shaopeng et al. [7] studied the changes of pavement wet-slip coefficient and pavement anti-slip performance under severe weather conditions such as different water depth, different snow thickness and different icing thickness. Guo Zhongyin et al. [8] used SPSS software to study the influencing factors and quantitative relationship of wet sliding performance of typical pavement structure under the adhesion conditions of ice water mixture through analysis of variance and multiple linear regression analysis. Wang Lei et al. [9] proposed the threshold value of anti sliding value and traffic volume recommended value. Li Lanlan [10] et al. Established the classification prediction method of highway road wet sliding index and road icing index, and gave the classification standard. Li Changcheng et al. [11] proposed the concept of pavement wet sliding index, and established the relationship between the actual pavement friction coefficient and the description phenomenon of wet pavement. Skarie [12] relieved the vehicle from
slipping on wet roads by rapidly deploying a specially designed traction medium (TM). Meyer W.E. [13] discussed pavement design and other factors that inhibit or promote water slide, as well as possible remedial measures. Hosking, J.R. [14] considered various factors that lead to pavement sliding, gave the estimation of their size, and discussed the methods to reduce the changes caused by these factors. In order to solve the problem of wet pavement, some scholars have conducted in-depth research on the treatment measures of wet pavement [15-17].

Obviously, there is still a lack of research on the main influencing factors of pavement wet sliding phenomenon in tunnel. The road surface in the tunnel is very easy to cause traffic accidents and cause heavy losses. Therefore, more and more attention has been paid to the prevention and control of tunnel pavement. However, in order to prevent the tunnel pavement from being wet, it is necessary to know the influencing factors. In view of this, based on Baojiashan tunnel, using a variety of detection means including the establishment of meteorological monitoring network, the main influencing factors of tunnel wet sliding phenomenon are found out, and feasible guidance measures are put forward for traffic safety and operation.

2. Project overview and monitoring point layout
Baojiashan super long tunnel is located at the throat of Xiaohe -Ankang expressway, passing through Qingshan and yuhuangshan mountains in Qinling Mountains. It has rugged and dangerous terrain, dense vegetation, complex geological structure and changeable geological lithology, with a total length of 11.2km. The annual precipitation in the area is 800-950mm, and the rainy season is generally concentrated from July to September, with the characteristics of cold spring, summer drought, summer flood and autumn flood. (figure.1)

Figure.1 Geographical location of Baojiashan super long tunnel.

A total of 7 meteorological monitoring stations are set up inside and outside Baojiashan tunnel, and the specific locations are shown in figure. 2. There are 3 monitoring points outside the tunnel, which are located at ZK163 + 100 (the south entrance of the tunnel), ZK151 + 400 (the north exit of the tunnel) and the mountainside on the north exit of the tunnel; Four monitoring stations are set up in the tunnel, which are located at ZK162 + 480, ZK158 + 050 (at the ventilation shaft of the tunnel), ZK155 + 450 (in the middle of the tunnel) and ZK152 + 000 (300m away from the north exit in the tunnel).

Figure.2 Detailed distribution of meteorological monitoring stations.
3. Cause analysis of the wet slip phenomenon in the tunnel

Based on the investigation of wet sliding phenomenon in long tunnels of Xihan Expressway, Xikang Expressway and Shitian Expressway, the geographical location and regional climate characteristics, length, trend and ventilation condition of tunnels in Qinba mountain area are understood. Combined with the analysis of relevant data, it is concluded that the main influencing factor of tunnel wet sliding phenomenon is air relative humidity, air temperature, temperature difference inside and outside the tunnel and wind speed.

3.1. Analysis on the relationship between wet sliding phenomenon and air relative humidity in tunnel

In 2013, 2014 and 2015, continuous monitoring was carried out for each observation point in the tunnel, and the daily average relative humidity of each observation point in July and August was drawn as a curve. Since the trend of relative humidity curve in July and August of the three years is basically similar, only the relative humidity curve of July and August in 2013 is listed here (figure. 3 and figure. 4).

![Figure.3 Daily average relative humidity of each measuring point in July 2013.](image1)

![Figure.4 Daily average relative humidity of each measuring point in August 2013.](image2)

According to the comparative curve analysis of daily average relative humidity of each observation point in the tunnel, the following conclusions are drawn:

1) The daily average relative humidity of ZK158 + 50 (tunnel inner vent) and ZK162 + 480 (south entrance of tunnel) in July and August of two years basically maintained above 80%.

2) In July and August of 2013, 2014 and 2015, the average air relative humidity of ZK155 + 450 (middle part of the tunnel) observation point reached 97%, and the air humidity was in saturated state for a long time. Water vapor was easy to condense on the ground and the inner wall of the tunnel with lower temperature, resulting in wet sliding phenomenon.

3.2. Analysis on the relationship between wet sliding phenomenon and air temperature in tunnel

According to the monitoring data of each observation point in the tunnel, the daily average temperature curves of July and August in 2013, 2014 and 2015 are plotted in figure. 5-10.
Figure 5 Daily average temperature of each measuring point in July 2013.

Figure 6 Daily average temperature of each measuring point in August 2013.

Figure 7 Daily average temperature of each measuring point in July 2014.

Figure 8 Daily average temperature of each measuring point in August 2014.
According to the comparison curve analysis of daily average relative humidity in the tunnel, the following conclusions are obtained:

1) The daily average temperature of ZK163 + 100 (South portal outside the tunnel) in July and August of these two years is significantly higher than that of ZK155 + 450 observation point inside the tunnel, and the wet sliding phenomenon is the most serious in July and August.

2) When the temperature outside the tunnel is greater than that inside the tunnel, the greater the temperature difference, the air relative humidity will increase until it reaches the saturation state. If the temperature difference further increases, the air will have condensate water precipitation from the air; otherwise, the relative humidity will decrease with the increase of temperature, which is an important reason for the tunnel to be wet and slippery.

3.3. Analysis of relationship between rainfall and wet sliding in tunnel

Figure 11 shows the corresponding map of the wet sliding observation and precipitation observation in the tunnel from June to August 2013. It can be seen from the figure that there was precipitation outside the tunnel when the wet phenomenon occurred in 11 days from June to August, and there was no precipitation outside the tunnel when the wet phenomenon occurred in 31 days, so there was no obvious statistical relationship between the tunnel wet sliding phenomenon and the rainfall.

Figure.11 Corresponding map of zk153 + 500 wet sliding observation and precipitation observation in tunnel from June to August 2013.
3.4. Analysis of wind speed and wet sliding in tunnel

Figure 12 shows the corresponding map of daily average wind speed at ZK155+450 and ZK153+500 wet sliding observation in the tunnel from June to August 2013. It can be seen from the figure that the daily average wind speed in the tunnel from June to August varies from 0.3 to 1.5 m/s.

According to the principle of condensation, the wind speed in this section is the wind speed suitable for condensation, and the wet sliding phenomenon exists in most of the time during the investigation, which also confirms this theory. According to the investigation results of the wet sliding phenomenon in the tunnel from Xi'an to Hanzhong of Beijing Kunming Expressway, the average wind speed of the investigated tunnels reaches 5.58 m/s, and the whole section of the road is dry. This shows that when the wind speed is high to a certain extent, it is conducive to alleviate the phenomenon of wet sliding.

3.5. Analysis of the relationship between air pressure in the tunnel and wet slip in the tunnel

Figure 13 shows the corresponding table of daily air pressure and ZK153+500 wet sliding observation in the tunnel from June to August 2013. It can be seen from the table that the daily average air pressure in the tunnel varies from 931.2 to 945.1 MPa from June to August, and the wet sliding phenomenon occurs in the tunnel when the daily average air pressure on July 2 and August 26 is 931.2 and 945.1 MPa, which indicates that there is no inevitable correlation between the level of tunnel air pressure and the wet sliding phenomenon.

Figure 13 Corresponding diagram of the ZK153+500 wet slip observation and air pressure observation in the tunnel from June to August 2013.
3.6. Other influencing factors of wet sliding in tunnel

1) The tunnel is an extra long tunnel. According to the existing research results, it is not easy to have wet sliding when the tunnel length is less than 2km, and it is easy to appear wet sliding when the tunnel is too long and the ventilation index is low.

2) The additional discharge and grit chamber in the tunnel may aggravate the wet sliding phenomenon to a certain extent. Three discharge and grit chambers are set up between the two main tunnels in the middle of Baojiashan tunnel. According to the observation, this section is also the most serious section with moisture regain, which indicates that the existence of discharge and grit chamber aggravates the wet sliding phenomenon of the tunnel to a certain extent.

3) The arch wall of the tunnel is made of concrete lining, the bottom is concrete pavement, and the side walls of both sides are paved with 3m high decorative tiles, which limit the moisture absorption capacity of the tunnel itself. The comparison of lining in tunnel, cement concrete pavement and asphalt concrete section shows that decorative tiles, cement concrete lining and concrete pavement have adverse effects on tunnel wet sliding and moisture regain.

4. Analysis of the physical mechanism of the tunnel wet slip phenomenon

Relative humidity refers to the ratio of the absolute humidity in the air to the saturated absolute humidity at the same temperature, and its value shows the degree of saturation of water vapor. When the relative humidity of the air exceeds 100%, the excess water vapor will generally condense. As the temperature increases, the capacity of water vapor in the air is higher, that is, when the water vapor content in the air is the same, the relative humidity will decrease when the temperature increases.

When the temperature inside the tunnel is higher than that outside the tunnel, the temperature of the air outside the tunnel begins to rise after entering the tunnel, and the ability of the air to contain water vapor is enhanced. In the absence of water vapor supplement, the relative humidity of the air will decrease; When the temperature inside the tunnel is lower than the outside of the tunnel, after the air outside the tunnel enters the tunnel, the temperature of the air begins to decrease, the capacity of the air to contain water vapor decreases, and the relative humidity of the air increases. Under high-temperature and high-humidity weather conditions, after the air outside the tunnel enters the tunnel, as the temperature gradually decreases, the air water vapor gradually becomes saturated, and excess water vapor will condense out, and then condense on the ground and inner wall of the tunnel, causing the tunnel Slippery phenomenon.

Assuming that the quality of the water vapor contained in the air is unchanged, after the air with different relative humidity outside the tunnel enters the tunnel, as the air temperature decreases, the air humidity gradually increases to reach a saturation state, and the value of this air temperature drop is called Temperature Drop Critical Value.

In order to get the relationship between the relative humidity of the air outside the tunnel and the critical value of the temperature drop, early warning is made for the wet sliding phenomenon of the tunnel.
tunnel. Now, the relative humidity of the air outside the tunnel is 50%, 51%,..., 95%, and the critical values of temperature drop when the air temperature drops to 16 ℃, 17 ℃, 18 ℃, 19 ℃ and 20 ℃ respectively and the air reaches the saturation state under each relative humidity, and forms a sequence to fit the empirical formula for the critical value of air temperature decline when the air humidity reaches saturation state outside the tunnel after the air humidity reaches saturation state (see Figure 14).

It can be seen from Figure 14 that when the air outside the tunnel enters into the tunnel, the air humidity reaches the saturation state, and the critical value of the air temperature decrease shows a logarithmic function relationship with the relative humidity of the air outside the tunnel:

\[ y = -17.667 \ln(x) + 81.236 \]  
(1)

Where: x is relative humidity of air outside the tunnel; y is air temperature difference between inside and outside the tunnel.

It can be seen from formula (1) that the phenomenon of water vapor condensation in the tunnel is related to the relative humidity of the air outside the tunnel, the air temperature inside the tunnel and the difference between the air temperature outside the tunnel. The greater the relative humidity and temperature difference outside the tunnel, the more serious the wet sliding phenomenon is.

According to formula (1), the early warning table of tunnel wet sliding phenomenon (Table 1) can be compiled, that is, when the air relative humidity is within a certain range, the temperature difference between inside and outside the tunnel may reach a certain degree, which is helpful to do a good job in the early warning of tunnel wet sliding phenomenon and take corresponding measures.

Table 1. Warning table of tunnel wet sliding phenomenon

| Air Relative Humidity | Temperature difference between inside and outside the tunnel℃ |
|----------------------|--------------------------------------------------------------|
| 60%-70%              | 6-9                                                          |
| 70%-80%              | 4-6                                                          |
| 80%-90%              | 2-4                                                          |
| >90%                 | <2                                                           |

5. Prevention and control measures
1) Strengthen the tunnel ventilation, improve the humidity in the tunnel, prevent or reduce the phenomenon of wet sliding.
2) Grasp the meteorological information at any time, keep the information symmetrical, unimpeded, and formulate the safety guarantee measures of tunnel pavement anti sliding.
3) Strengthen the inspection of key and dangerous road sections and frequency, timely discover and eliminate dangerous situations, and strengthen the traffic control of wet and slippery sections and sections with frequent traffic accidents.
4) Improve the friction resistance of the pavement, perform groove or cover treatment on the cement concrete pavement, and remove the accumulated water in time to prevent slipping.

6. Conclusion
1) The wet slip phenomenon in the tunnel has no obvious relationship with the wind direction, rainfall and air pressure changes of the tunnel, mainly related to the meteorological conditions of high temperature and high humidity outside the tunnel, and the wind speed of the tunnel ventilation.
2) According to the actual observation data of Baojiashan Tunnel, the relationship between the relative humidity of the air outside the tunnel and the temperature difference between the inside and outside of the tunnel is obtained. A warning table for the wet slip phenomenon of the tunnel is given, which provides a basis for predicting the wet slip phenomenon and the countermeasures.
3) On the basis of the research on the mechanism of wet sliding phenomenon in the tunnel, considering the factors of anti sliding, traffic control and management of tunnel pavement, the paper
puts forward the safety guarantee measures for the anti sliding of tunnel pavement, strengthening the traffic control of the slippery section and the section with frequent traffic accidents, grooving or cover treatment of cement concrete pavement, strengthening tunnel ventilation and other measures to ensure the safety of tunnel operation.

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