Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 1, No. 3, 2022

The Control Standard for Settlement of Pavement Based on the Model of Acceleration Interference

Sen Liu[1, *], Haiying Huang[1]

[1]School of Civil Engineering, Henan Polytechnic University, Jiaozuo, China
[*]Corresponding author: Sen Liu (Email: 1809175902@qq.com)

Abstract: The control standard of pavement settlement caused by urban tunnel excavation is the focus of academic research at present. The establishment of settlement control standard gradually develops from safety control standard to comfort control standard. Based on the acceleration interference model, this paper presents a method to determine the pavement settlement control datum caused by the new tunnel penetrating the existing highway. Firstly, the vibration acceleration along the vertical direction of the road was selected as the comfort index, and the ideal sine function and Peck formula were used to describe the longitudinal curve of the road surface and the characteristics of the road surface settlement groove caused by tunnel construction. Secondly, considering the acceleration interference model, based on theoretical derivation, the calculation formula of vertical acceleration under the influence of road surface smoothness is obtained. According to superposition principle, the calculation formula of vertical acceleration under the influence of road surface smoothness and tunnel excavation is obtained. Thirdly, based on the relationship between acceleration value and subjective feeling of human body, the determination formula of pavement settlement control benchmark is proposed. The results show that the control datum formula is consistent with the engineering practice. Reducing the speed and the width coefficient of pavement settlement groove are effective methods to improve the comfort.

Keywords: Acceleration interference, Comfort, Pavement settlement.

1. Introduction

With the further development of urbanization, the urban traffic network becomes more and more intensive, and a large number of new tunnels are built under the existing urban roads. The construction of the undercrossing highway by shield breaks the original equilibrium state of the stratum, causes uneven deformation of the surrounding stratum, resulting in the settlement of the pavement, deteriorates the roughness of the pavement, and affects the safety and comfort of drivers and passengers. Therefore, it is of great social and economic value to study the pavement settlement deformation caused by the new tunnel undercrossing the operation highway and to select the pavement settlement control benchmark scientifically and reasonably.

In the research field of underpass existing highway, most of the researches include jacking method of frame bridge [1, 2], roadbed deformation law [3] and roadbed reinforcement measures. However, there are few studies on the settlement control benchmark of the undercrossing existing road surface [4]. The most influential one is the empirical formula of surface settlement generated by underground excavation proposed by Peck in 1969, which has been widely used in the analysis of surface settlement deformation. In China, the concept of "ground loss" was put forward for subway construction, and several modified Peck formula was put forward for Shanghai subway construction, and settlement deformation was studied by using empirical formula method, model test method, field test method and numerical simulation method[5, 6]. These methods have obtained a lot of valuable research results in the influence of subway construction on the surrounding environment. Zhu Zhengguo et al.[7]formulated the road surface settlement control benchmark caused by railway tunnel undercrossing highway by combining the flatness requirements and settlement groove width coefficient [8] prediction model, but did not consider the influence of the included Angle between the new tunnel and the existing road surface on road surface settlement. Xu Lunhui et al. [9] established a vertical vibration acceleration interference model combined with the sinusoidal wave theory of road surface, which was applied to the evaluation of driving comfort, and analyzed the influence of road surface amplitude, wavelength and speed on acceleration interference and driving comfort. However, the model did not combine the influence of tunnel excavation on road surface settlement, so it was not suitable for engineering research. Jung joon, etc. [4] to the comfort of driving control standards as a starting point, at the same time, considering both the road is not flatness and surface subsidence caused by tunnel construction groove shape characteristic, based on theoretical derivation formula for calculating the settlement control benchmark was proposed, but doesn't take into account the acceleration interference in the process of the car model is established, the actual engineering application is not strong.

Acceleration disturbance is a description of vehicle speed swing, and the swing of vehicle speed is closely related to driving comfort. Therefore, in this paper, vibration acceleration in the vertical direction of driving is selected as the comfort index based on the acceleration disturbance model. Considering the influence of road surface flatness, road surface settlement caused by tunnel excavation and longitudinal Angle between road surface and tunnel, the acceleration interference model is established and the control benchmark formula is put forward. The actual calculation and engineering verification are carried out to provide theoretical basis for the evaluation and research of driving comfort.

2. Determination of Evaluation Indicators

2.1. Vibration Acceleration

In the process of vehicle driving, the vibration felt by drivers and passengers can be divided into three directions: front and back, left and right, and up and down, and the causes of vibration acceleration in different directions are different. Ride ride in cars drive on the road, its comfort mainly depends on its in the car on the total vibration acceleration, the vibration acceleration is along the direction of the car by the (X), the direction in the plane of the vertical (Y) and perpendicular to the direction of road pavement (Z) is determined by the superposition of vibration acceleration of the three directions. According to the international Organization for Standardization (ISO/TC108/SC4), the international standard "Guide to The Evaluation of Human Body subjected to whole body Vibration" was formulated on the basis of a large number of researches and literatures on human body subjected to whole body vibration. The total vibration acceleration for evaluating human comfort is called "weighted root mean square of acceleration", and its calculation formula is as follows:

$$\boldsymbol{a_w} = \sqrt{(\mathbf{1.4}\boldsymbol{a_{xw}})^2 + (\mathbf{1.4}\boldsymbol{a_{yw}})^2 + \boldsymbol{a_{zw}}^2} \tag{1}$$

Where $\boldsymbol{a_w}$ is the weighted root mean square of acceleration; $\boldsymbol{a_{xw}}$, $\boldsymbol{a_{yw}}$ and $\boldsymbol{a_{zw}}$ are the RMS of vibration acceleration of X(vertical), Y (horizontal) and Z (vertical) axes respectively.

2.2. Acceleration Interference

When a driver is driving on the road, the speed always changes or oscillates within a certain range. Acceleration interference is a description of the vehicle speed oscillation, which is closely related to driving comfort. It is found that the main cause of the forward and backward vibration acceleration is the speed change during the driving process. The cause of left-right vibration acceleration is mainly the vehicle vibration caused by uneven flatness on both sides of road during vehicle driving. The closest cause of the up-down vibration acceleration is the vehicle vibration caused by the uneven flatness of the road axis in the process of vehicle driving. At the same time, the vibration acceleration of up and down (vertical) direction is much larger than the other two directions, and has the greatest influence on comfort. Therefore, the vibration direction can only consider the influence of the vibration in the upper and lower directions on the driving comfort, that is, the best indicator of the roughness of the road is the vibration acceleration in the vertical direction.

2.3. Concept of Acceleration Interference

Herman put forward the concept of acceleration interference in 1950s, that is, the amplitude of vehicle velocity swing is expressed by the standard deviation of acceleration to average acceleration, and the greater the acceleration interference is, the worse the driving comfort will be. The units are the same as the units of acceleration. Its expression is:

$$\boldsymbol{\sigma_z} = \left\{\frac{\mathbf{1}}{\boldsymbol{T}}\int_{\mathbf{0}}^{\boldsymbol{T}}[\boldsymbol{a}(\boldsymbol{t_i}) - \overline{\boldsymbol{a}}]^{\mathbf{2}}\, \boldsymbol{dt}\right\}^{1/2} \tag{2}$$

In Equation (2), σ_z is acceleration interference; T is the total observation time; A (t_i) is the acceleration at time t; A 12 is the average acceleration, which is calculated as follows:

$$\overline{\boldsymbol{a}} = \frac{\mathbf{1}}{\boldsymbol{T}}\int_{\mathbf{0}}^{\boldsymbol{T}} \boldsymbol{a}(\boldsymbol{t})\boldsymbol{dt} \tag{3}$$

In this paper, vertical vibration acceleration interference is selected to evaluate the driving comfort of drivers and passengers.

3. Theoretical Basis of Influence of Acceleration Interference on Ride Comfort

Because the longitudinal section curve of ordinary actual road surface is very complicated random waveform, many scholars have proposed using waveform function to describe the uneven road surface in international publications and existing papers. M·W·Syaers proposed to use sine function to describe uneven road surface, which is the most widely used description method in existing literature. In the analysis of waveform road surface, it is considered that the profile curve is the ideal sine wave, that is, the profile curve of road surface is the ideal sine wave, and the road surface equation is:

$$\boldsymbol{Z}(\boldsymbol{t}) = \boldsymbol{Asin}(\boldsymbol{\omega t}) = \boldsymbol{Asin}\left(\frac{\mathbf{2}\boldsymbol{\pi}}{\boldsymbol{L}}\right) \tag{3}$$

Where, Z(t) is the longitudinal distance between the actual road surface and the road design line; A is the amplitude of sinusoidal road surface; L is the wavelength of sinusoidal road surface; X is the horizontal displacement of sine wave road surface.

Assuming that the speed is V, $x=vt$ can be obtained

$$\boldsymbol{Z}(\boldsymbol{t}) = \boldsymbol{Asin}\left(\frac{\mathbf{2}\boldsymbol{\pi v t}}{\boldsymbol{L}}\right) \tag{4}$$

After derivation, the expression of acceleration interference value is

$$\sigma_z = \frac{A}{T}\frac{2\pi v}{L}\left\{\frac{2\pi^2 v^2}{L^2} - \frac{\pi v}{2TL}\sin\left(\frac{4\pi vT}{L}\right) - \frac{1}{T^2}\left[\cos\left(\frac{2\pi vT}{L}\right) - 1\right]^2\right\}^{1/2} \tag{5}$$

4. Influence of Surface Settlement Caused by Tunnel Construction on Riding Comfort

4.1. Influence of Tunnel Construction on Surface Settlement

Settlement trough will appear in the vertical direction of the longitudinal axis during tunnel construction. Peck collected a large number of measured data in 1969, and believed that the ground subsidence caused by tunnel excavation was distributed in a Gaussian curve. He proposed the concept of ground loss and a practical method to estimate the ground subsidence caused by tunnel excavation. Peck believed that the volume of surface settlement trough formed by tunnel excavation without drainage should be equal to the ground loss. Peck formula is as follows:

$$S(x) = S_{max} exp\left(-\frac{x^2}{2i^2}\right) \quad (6)$$

Where S(x) is the surface settlement value at the point x away from the tunnel center line; S_{max} is the maximum surface settlement value at the center line of the tunnel; X is the horizontal distance from the center line of the tunnel; I is the width coefficient of surface settlement trough, namely, the horizontal distance from the reverse bending point of settlement trough curve to the center line of tunnel. The formula needs to determine S_{max} and i

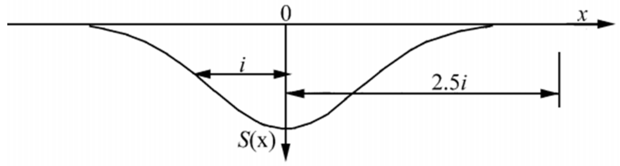

Figure 1. Horizontal distribution of surface subsidence

Among them

$$S_{max} = \frac{V_i}{i\sqrt{2p}} \approx \frac{V_i}{2.5i} \quad (7)$$

As for the surface settlement trough width coefficient I, there are many researches at home and abroad, and the general one can be expressed as

$$\frac{i}{D} = 0.575\left(\frac{z_0}{D}\right)^{0.9} \quad (8)$$

So I =0.575z_0 ^(0.9) D^(0.1). Where, D is the tunnel diameter; z_0 is the depth from the tunnel center to the surface.

After I is obtained, S_{max} can be obtained from Equation (7)-(8), and then the vertical settlement value of any point on the surface can be obtained through Equation (12).

4.2. Influence of Angle θ between Tunnel and Highway on Surface Settlement

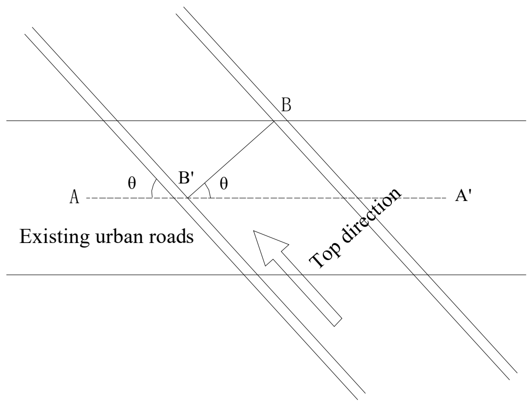

Figure 2. Diagram of Angle between road surface and underpass tunnel

As shown in Figure 2, the included Angle between the longitudinal axis direction (trend) of the existing highway and tunnel in actual engineering is θ, AA' is the longitudinal axis direction of the highway, BB' is the vertical direction of the tunnel, and the intersection Angle of AA' and BB' is recorded as γ. If only the roughness of road surface caused by tunnel construction is considered, the settlement curve along BB' direction is assumed to be an approximate normal distribution curve (in accordance with Peck formula), then according to Equation (6) and Figure 2, the road surface curve along the longitudinal axis of road surface caused by the influence of new tunnel construction can be expressed as:

4.3. Superimposed Influence of Existing Road Surface Roughness and Tunnel Construction

As shown in Figure 2, it is assumed that the road surface curve along the direction AA' is sinusoidal and the settlement curve along the direction BB' is approximately normal distribution. As mentioned above, Equation (8) shows that when only the roughness of the sinusoidal road surface is considered, the vibration acceleration of the vehicle in the vertical direction reaches the maximum value at the sinusoidal wave peak or trough. Equation (11) shows that when only considering the pavement settlement caused by tunnel construction, the vibration acceleration of the vehicle in the vertical direction reaches the maximum value at the maximum settlement. Therefore, when the trough of the sinusoidal curve coincides with the lowest point of the settlement curve, the vertical vibration acceleration caused by the two get the maximum value and are in the same direction, which is the most unfavorable combination of the two.

The expression of S_{max} is:

$$S_{max} = \left(\frac{a_{ymax}}{v^2} - 4\frac{\pi^2 A}{L^2}\right)\frac{i^2}{sin\theta} \quad (12)$$

5. Numerical Examples

This section mainly analyzes the calculation results of Equation (12) under different influencing factors and their influences on driving comfort.

5.1. Influence of the Angle θ between the Longitudinal Axis of the Expressway and the Tunnel on Driving Comfort

In order to study the influence of the included Angle θ on driving comfort, it is assumed that the tunnel buried depth is 10m, i =5m, S_{max}=40mm, amplitude A is 20mm, wavelength L is 30, 40, 50m, and wavelength is 20, 40, 60, 80, 100, 120km/h relative to velocity.

The boundary (plane) a_y=0.9m/s^2 of "some uncomfortable" and "uncomfortable" in the relationship between acceleration and subjective sensation of human body is also plotted in Figure 3, i.e., "some uncomfortable plane" in Figure 3. Thus, it can be roughly seen from Figure 3 that when θ is 30, 60 and 90 respectively, Different combinations of V and L correspond to whether the driving comfort is below or above the "somewhat uncomfortable plane".

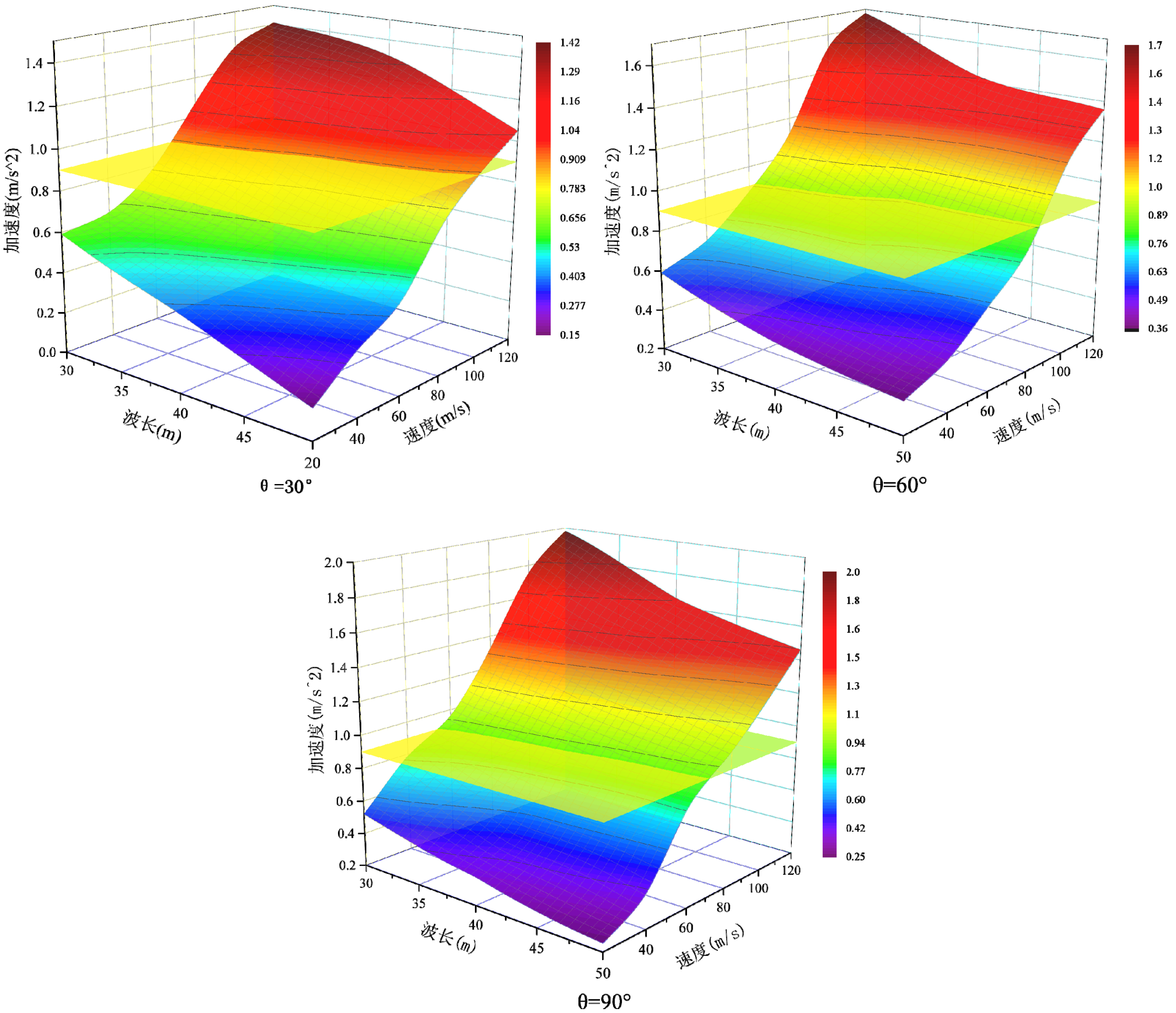

Figure 3. Influence of the Angle θ between the longitudinal axis of the expressway and the tunnel on driving comfort

It can be seen from Figure 3 that the acceleration A_ymax is proportional to the driving speed V, inversely proportional to the wavelength L, and inversely proportional to the longitudinal Angle θ of the existing road and tunnel, both of which present a linear relationship. The maximum a_ymax value increases from 1.41 to 1.68m/s^2 with the increase of 19.1% as the longitudinal Angle θ of the existing road and tunnel increases from 30 degrees to 60 degrees. With the longitudinal Angle θ increasing from 60° to 90°, a_ymax increases from 1.68 to 1.98m/s^2, increasing by 17.8%. This shows that the greater the included Angle, the higher the driving speed and wavelength are required to improve the driving comfort, which is consistent with the actual feeling of driving and riding. Given the included Angle and wavelength, the method to improve driving comfort is to reduce driving speed; Given the speed and wavelength, the method to improve the driving comfort is to control the longitudinal Angle between the existing road and tunnel; Given the Angle and speed, the method to improve driving comfort is to control the wavelength.

5.2. Influence of Amplitude on Driving Comfort

In order to study the influence of amplitude A on driving comfort, the tunnel depth is assumed to be 10m, i =5m, S_{max}=40mm, and the longitudinal Angle θ between the existing road and tunnel is 60 degrees. Wavelength L is set as 30, 40 and 50m, and wavelength is set as 20, 40, 60, 80, 100 and 120km/h relative to velocity.

The boundary between "somewhat uncomfortable" and "uncomfortable" (plane) a_y=0.9m/s^2 and the boundary between "extremely uncomfortable" (plane) a_y =2.0m/s^2 in the relationship between acceleration and human subjective sensation are also plotted in Figure 5. For high-grade highways, amplitude A generally varies from 5 to 100mm. To study the effect of amplitude of driving A comfort, amplitude to be taking A: 20, 40, 60 mm, so by figure 5 can see roughly with different sets of L and v corresponding driving comfort is below the "some uncomfortable plane" or above, also can see different L and v combinations corresponding driving comfort whether have reached extremely comfortable flat.

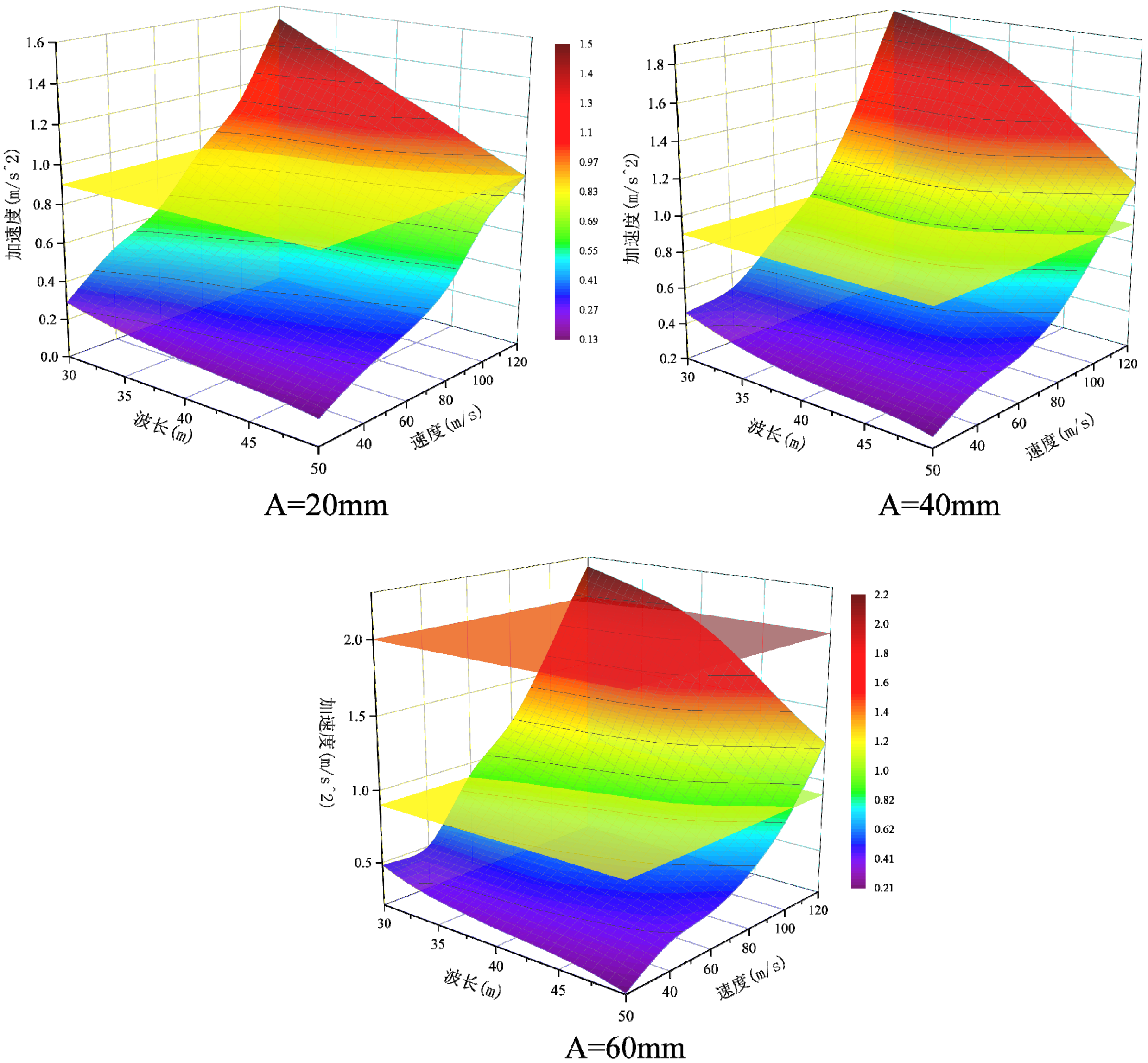

Figure 4. Influence of amplitude on driving comfort

As can be seen from Figure 5, Aymax is directly proportional to driving speed V, inversely proportional to wavelength L, and directly proportional to amplitude A, all of which present A linear relationship. With the amplitude A increasing from 20mm to 40mm, the maximum aymax increases from 1.53 to 1.89m/s^2, increasing by 23.5%. As the amplitude A increases from 40mm to 60mm, aymax increases from 1.89 to 1.98m/s^2, increasing by 17.8%. This shows that the greater the amplitude is, the higher the requirements of driving speed and wavelength for improving driving comfort are, which is consistent with the actual feeling of driving and riding. Given the speed and wavelength, the method to improve driving comfort is to control the amplitude; Given speed and amplitude, the method to improve driving comfort is to control the wavelength; Given the wavelength and amplitude, the method to improve driving comfort is to reduce driving speed.

6. Conclusion

Based on the acceleration interference model, a relatively complete solution to the problem of road surface settlement control benchmark caused by new tunnel is proposed from the control standard of vehicle comfort. Finally, the calculation formula of maximum vertical vibration acceleration of vehicle and the determination formula of road surface settlement control benchmark are given A_ymax acceleration is proportional to the driving speed v, with both the highway profile curve is directly proportional to the wavelength L inversely proportional relationship, and the width of the road surface subsidence caused by tunnel excavation slot coefficient inversely proportional relationship, and is proportional to the amplitude of relationships, with both the road and tunnel longitudinal Angle theta proportional relationship, and the inverse proportion relationship between the square of the driving speed.

Given amplitude and wavelength, the method to improve driving comfort is to reduce driving speed; Given speed and amplitude, the method to improve driving comfort is to control the wavelength; Given wavelength and speed, the method to improve driving comfort is to control amplitude.

Reducing the speed and the width coefficient of pavement settlement groove are effective methods to improve the comfort.

References

[1] Z C Wang,Zhao Hu,Jinxing Lai,Hao Wang,Ke Wang,Wenbo Zan. Settlement Characteristics of Jacked Box Tunneling underneath a Highway Embankment[J]. Journal of Performance of Constructed Facilities,2019,33(2):

[2] P C Bai. Settlement Control Techniques of the Super-shallow Buried Large-span Mined Tunnel underneath an Existing Tunnel[J]. MODERN TUNNELLING TECHNOLOGY. 2020, 57(03): 175-181.

[3] L Yi. Study on the Influence Zoning of the New Urban Tunnel under the Existing Road [J]. Chinese Journal of Underground Space and Engineering. 2020, 16(05): 1490-1497.

[4] J Zhen, Z J Ding,elt. Control standard for settlement of pavement caused by a new tunnel passing underneath an existing highway [J]. JOURNAL OF HARBIN INSTITUTE OF TECHNOLOGY. 2020, 52(03): 51-58.

[5] D Qiao,Q L Ren. Study on the Influence of Subway Tunnel Construction on Existing Urban Roads [J]. Highway Engineering. 2019, 44(04): 158-162.

[6] P B Cui,J J Chen. Analysis on influence of ground surface settlement on highway with high-speed railway tunnel passing below[J]. JOURNAL OF JIANGSU JIANZHU INSTITUTE. 2015, 15(02): 21-25.

[7] Z G Zhu,S Huang,Y Q Zhu. Study of road surface settlement rule and controlled criterion for railway tunnel undercrossing highway [J]. Rock and Soil Mechanics. 2012, 33(02): 558-563.

[8] X Han, W L Luo,N Li. The Width of Settlement Trough Influenced by Tunneling in Soft Ground [J]. Chinese Joumal of Underground Space and Engineering, 2009(A6):7.

[9] L H Xu, C C Song. A Study on Evaluation of Pavement Roughness and Riding Comfort Based on Acceleration Noise Model [J]. Science Technology and Engineering. 2017, 17(02): 116-119.