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Numerical simulation study on ground settlement of underground tunnel caused by vehicle load

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Abstract
In order to study the influence of vehicle load and tunnel construction coupling on tunnel surface settlement in soft surrounding rock area, a three-dimensional model was established using MIDAS GTS NX software in the background of an airport tunnel project, and the influence of vehicle load on the ground settlement of single tunnel and double tunnel projects was studied. The results of the research shows that: during the tunnel excavation, the effect of vehicle load on the upper road will cause additional settlement of soil. With the increase of driving speed and vehicle load, the maximum ground settlement increases accordingly. However, the increase of driving speed and vehicle load will not cause the change of the trend of surface settlement curve. The surface settlement curve in single tunnel project is "V" type, and the surface settlement curve in double tunnel project is "W" type. In the double tunnel project, the vehicle load makes the soil above the left leading tunnel produce greater additional settlement, resulting in greater uneven settlement of the soil above the two tunnels. In order to ensure normal passage and to meet the construction safety, the driving speed of vehicles passing above shall be controlled to not exceed 20km/h, and the vehicle load shall not exceed 100kN; in the double tunnel project, due to the increase in surface settlement is greater, the vehicle passage on the road above the tunnel should be strictly restricted or prohibited.

Keywords:*vehicle load; single-track tunnel; double-track tunnel; surface subsidence; numerical simulation*

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I. INTRODUCTION

With the rapid development of underground space development and utilization technology in China, more and more projects are crossing existing highways, railways and airports. In order to meet people's traffic needs, highways, railways and airports usually keep normal operation during tunnel construction, which greatly increases the safety requirements and construction difficulties of construction design, and also ensures that construction will not affect the normal traffic of the upper pavement[1].In addition to imposing its own gravity load on the road surface, the driving vehicle also generates vibration on the road surface, which results in dynamic pressure on the road surface. Therefore, these factors must be considered in the construction design analysis.

Tang Zheng[2] et al. analyzed the variation rule of ground settlement during pipe curtain method group pipe jacking construction based on an example of Tianlin Road underpass Middle Ring Tunnel Project in Shanghai.Zude[3] et al. analyzed the influence of foundation form, stiffness of building, angle between building and tunnel, distance between building centre axis and tunnel centre axis on pavement settlement during tunnel construction through numerical simulation.

Zhang Zhiguo[4]et al. established a numerical model of surrounding Rock-tunnel structure based on a domestic high-speed railway tunnel project and analyzed the stability law of jointed lining structure under the influence of different kinds of fibers, vehicle speed and surrounding rock grade. Vehicle model established by D Cenbon et al. [5]has been widely used. The dynamic load pressure coefficient generated by the model on the road surface is calculated and converted into standard axle load by this coefficient.Zhang Wenjie[6]simplified heavy traffic dynamic load to excitation form reflecting load cycle characteristics, driving speed and smoothness of Audit Department, and simulated it with numerical analysis software. The result shows that heavy traffic dynamic load will cause the increase of ground settlement, and the relative increase of additional ground settlement is approximately linear with vehicle driving speed. The effect of small vehicles is small and can be ignored.

Shao Zhushan et al.[7]Carried out transient analysis of vehicle load using ANSYS software, and proposed that the vibration response of initial support structure gradually increases with the increase of vehicle driving speed. Song Zhengping[8] used MIDAS GTS NX to carry out numerical simulation for Guiyang Metro

Line 1 through the expressway section around the city by different construction excavation methods. The simulation results show that CRD method can control the settlement of pavement and tunnel vault well.

At present, domestic and foreign scholars mainly study the settlement changes of single and double-track tunnels under static load and the influence of dynamic load on tunnel structure, but seldom study the influence of vehicle load and tunnel construction coupling on tunnel surface settlement. Based on an example of an airport tunnel project, this paper discusses the influence of vehicle load on ground settlement through a three-dimensional model established by finite element software MIDAS GTS NX, which mainly includes vehicle speed and vehicle load. At the same time, the influence laws of vehicle load on ground settlement of single tunnel and double tunnel are compared and analyzed.

II. ENGINEERING OVERVIEW

An Airport Tunnel project is composed of an airport station (underground station) and an entrance tunnel with a total length of 4535m. The ground elevation of the project site is about 110-140 m, and the corresponding elevation of tunnel buried depth is about 10-19 M. In this paper, the 100m section of the section introduced into the section tunnel by Chengdu Railway is selected as the research object. The section crosses G322 National Highway underneath and is constructed by undercut method with Vc-type composite lining. The construction section belongs to soft surrounding rock geology. The site soil layers mainly include 1-2 plain fill (Q4ml), 1-5 gravel soil (Q4ml), 9-2 strong weathering layer (J1w) and 9-3 weathering layer (J1w).

III. FINITE ELEMENT MODEL ESTABLISHMENT

In this paper, finite element software MIDAS GTS NX is used to establish tunnel construction model. All soil layers are simplified to homogeneous soil layers. See Table 1 for physical and mechanical parameters of soil layers. The soil boundary of the simulated numerical model is 3-5 times the tunnel diameter from the tunnel center line and the size of the single tunnel model is 100m× 70m × 35m, double tunnel model sizeis150m × 70m × 35m. Moore-Coulomb model is used for soil mass and elastic model for support structure. The structural parameters are shown in Table 2. CRD excavation method is used for tunnel excavation. The buried depth of the tunnel is 10m, of which the net distance between the two tunnels is 15m. The left tunnel is excavated first and the right tunnel is excavated after the excavation footage reaches 15m.

Tab. 1 Mechanical parameters of soil mass

Soil Number	Name of soil layer	d/m	E/(kN/m^2)	υ	γ (kN/m^3)	c/kPa	ϕ /°	K_0	κ/(m/d)	e_0
1-2	Plain fill	3	6630	0.3	19.71	5	6	0.43	1.74E-07	0.67
1-5	Gravels	4	34500	0.2	19.61	0.5	25	0.25	0.00058	0.5
9-2	Strongly weathered argillaceous sandstone	8	93085	0.17	23.63	0.58	45.6	0.2	0.000463	0.42
9-3	Medium weathered argillaceous sandstone	55	138000	0.17	24.03	1.07	37.3	0.2	1.62E-06	0.5

Tab. 2 Supporting structure parameters

Structure Name	E/(kN/m2)	υ	γ /(kN/m3)	c /kPa	ϕ /°
Advanced support	133056.8	0.17	24.62	0.68	46.93
Initial support	23000000	0.2	22		
Secondary lining	32500000	0.2	25		
Temporary support	23000000	0.2	22		
Inverter filling	28000000	0.2	23		
Close the face of the palm	23000000	0.2	22		
Bolt	210000000	0.3	78.5		

IV CALCULATION MODEL OF VEHICLE LOAD

For the simplification of the dynamic model of vehicle load, many scholars at home and abroad have studied it. At present, the simplification methods are roughly divided into: concentrated load, rectangular wave load, impact load, sine wave load and random load [9][14]. Among them, random load is the most ideal model, which is based on a large number of measured data and can integrate the influence of different factors such as road roughness, vehicle speed and vehicle type. However, due to its strong limitations and complex operation, it requires a lot of computing resources, so it is not usually used in the simulation process.In this paper, the sine wave load model with higher tendency of many scholars is used to simulate the vehicle load, and its load expression [15] is as follows:

$$F(t) = P_0 + P_d \sin(\omega t) \quad (1)$$

Where, P_0 is the static load of vehicle, P_d is the amplitude of dynamic load, and the calculation formula is:

$$P_d = M_0 \alpha \omega^2 \quad (2)$$

Where, M_0 is the vehicle unsprung mass, $\alpha$is the geometric irregularity vector height, usually taken as 2mm, the vibration circumference $\omega = 2\pi\upsilon / L$, L is the vehicle length, and$v$ is the vehicle running speed.

Considering the construction conditions nearby, the truck is mainly used as the traffic vehicle, and the unsprung mass of the vehicle is taken as5kN·s^2/m. Refer to *the Technical Standard for Highway Engineering* (JTG B01-2014)[16]. The outline dimensions of the truck are shown in Figure 1, L=12m, and the front wheel landing length and width are 0.3m × 0.2m, the length and width of the middle rear wheel landing is 0.6m × 0.2m, that is, the area of vehicle load action isA=0.3×0.2×2+0.6×0.2×4=0.6m^2.

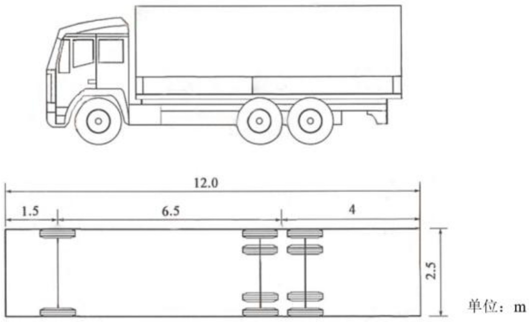


Figure1Outline dimension diagram of truck

The size of the stress in each case shall first calculate the size of the total load and the size of the load area, and then calculate the size of the stress per unit area, that is

$$P(t) = \frac{F(t)}{A} = \frac{P_0 + P_d \sin(\omega t)}{A} \quad (3)$$

During dynamic analysis, the free field boundary provided by MIDAS GTS NX is used to control the boundary constraint conditions of the model. In order to effectively reduce the reflection effect of the boundary, set the top surface as free, the bottom surface as fixed, and the other surfaces as free field boundaries. The vehicle has friction with the ground during driving, so the damping ratio is set to 0.314. The loading model of vehicle load is shown in Figure 2. With reference to the relative position relationship between G322 National Highway and the tunnel in the actual project, the position relationship between the road surface and the tunnel in the numerical simulation process is analogously set. At the same time, in order to more intuitively analyze the impact of vehicles on the surface settlement, the location of the surface settlement curve is selected as the middle of the width of the model, that is, the vehicle load is just above the tunnel.

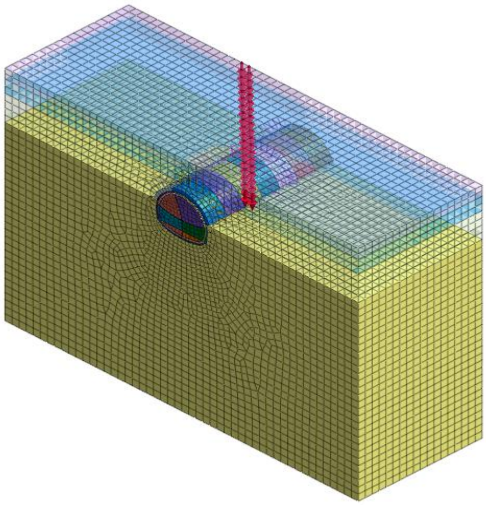


Figure2 Numerical model of vehicle load

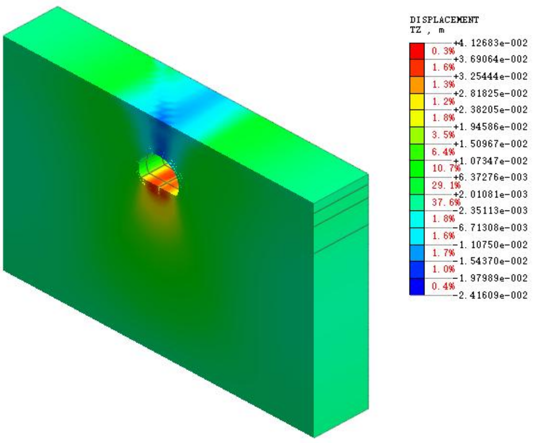
V ANALYSIS OF FACTORS AFFECTING SURFACE SUBSIDENCE

In this paper, the analysis of the factors affecting the surface subsidence by vehicles mainly includes two aspects: driving speed and vehicle load. When analyzing the influence of running speed, control the static load of the vehicle to be 100kN unchanged, and change the vehicle speed to be 20km/h, 40km/h and 60km/h respectively; When analyzing the impact of vehicle load on ground settlement, under the optimal driving speed, change the vehicle static load to 100kN, 200kN, 300kN respectively. Under the condition of optimal driving speed and vehicle load, the influence of vehicle load on ground settlement in single tunnel and double tunnel projects is further analyzed.

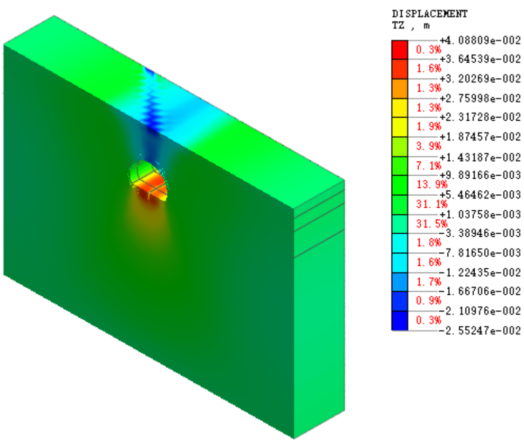
5.1 Study on the influence of driving speed on surface subsidence

Control the static load of the vehicle to be 100kN and change the vehicle speed to be 20km/h, 40km/h and 60km/h respectively, as shown in Figure 3, which is a three-dimensional settlement displacement comparison diagram under no load on the ground and three different speeds.

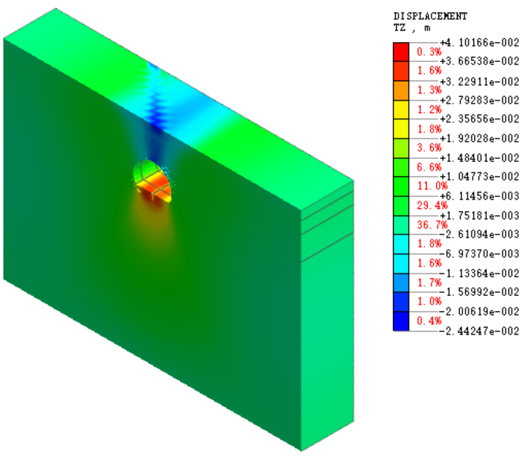
It can be seen from Figure 3 that when there is a vehicle load with a speed of 20km/h above the tunnel, the maximum settlement value of the soil mass increases slightly. However, due to the slow speed of the vehicle at this time, the vibration effect of the vehicle on the road surface is small, so the impact on the settlement is small. Along the action line of vehicle load, where there is vehicle load on the surface, the settlement value also increases correspondingly and fluctuates; When the vehicle load is directly above the tunnel, that is, at the center of the width of the model, the settlement of the vault will reach the maximum value. When the driving speed is 40km/h, the driving speed of the vehicle increases, and its vibration on the pavement increases, resulting in further increase of soil settlement.



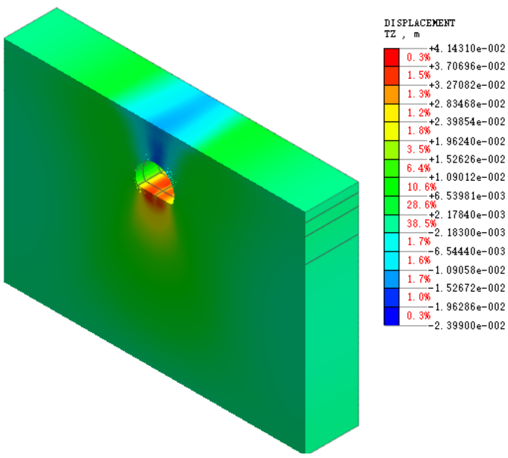
（a）3D settlement displacement nephogram without vehicle load



（b）3D settlement displacement nephogram at 20km/h



（c）3D settlement displacement nephogram at 40km/h



（d）3D settlement displacement nephogram at 60km/h

Figure3 Three dimensional settlement displacement nephogram without Vehicle Load and Different Vehicle Speed

When the driving speed is 60km/h, compared with 40km/h, the maximum settlement value increases by about 1.1mm. The settlement at the loading position of the vehicle on the surface further increases, and the scope of influence increases. It shows that when the vehicle speed is 60km/h, the disturbance to the soil is greater, and the settlement value of the soil is also relatively increased. In the four cases, the maximum settlement value of three-dimensional settlement displacement nephogram increases from 24.0mm without vehicle load to 25.5mm with driving speed of 60km/h, an increase of 6.25%, and the relative increment is not large, indicating that the change of vehicle speed has little impact on three-dimensional maximum settlement, but increases the settlement range.

Figure 4 is a comparison chart of the surface settlement curve without vehicle load and at different driving speeds. It can be seen from the figure that the effect of vehicle load does not affect the change trend of the surface settlement curve, and the change trend is the same in all four cases. The maximum settlement value of the curve is obtained at the center line of the tunnel, and the settlement value gradually decreases to both sides, and there is a certain amount of uplift at the side of the tunnel arch shoulder. The existence of vehicle load has little influence on the amount of uplift. When there is vehicle load on the ground surface, there is a maximum settlement on both sides of the tunnel centerline, mainly because the vehicle load is simplified as a local action caused by the force acting on the node in the numerical simulation. The comparison of surface settlement curves caused by driving speeds of 20km/h, 40km/h and 60km/h shows that with the increase of vehicle driving speed, the maximum surface settlement value increases from 13.7mm without vehicle load to 18.0mm, 22.6mm and 27.1mm, increasing by 31.4%, 65.0% and 97.8% respectively.Therefore, when excavating the tunnel, whether there are vehicles passing on the upper pavement and the vehicle speed have a great impact on the surface settlement and construction safety. In the actual project situation, the existing road traffic environment around the project should be reasonably controlled by integrating various factors. Under the project conditions studied in this paper, due to the proximity to the airport, the traffic demand is large, and the requirements for ground settlement are high, in order to meet the needs of all aspects at the same time, the driving speed of vehicles passing through the space intersection of G322 National Highway and the tunnel shall not exceed 20km/h.

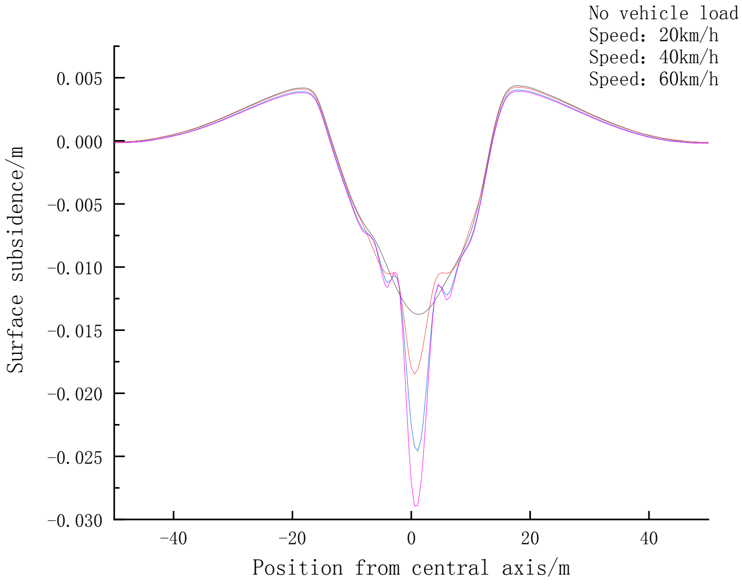
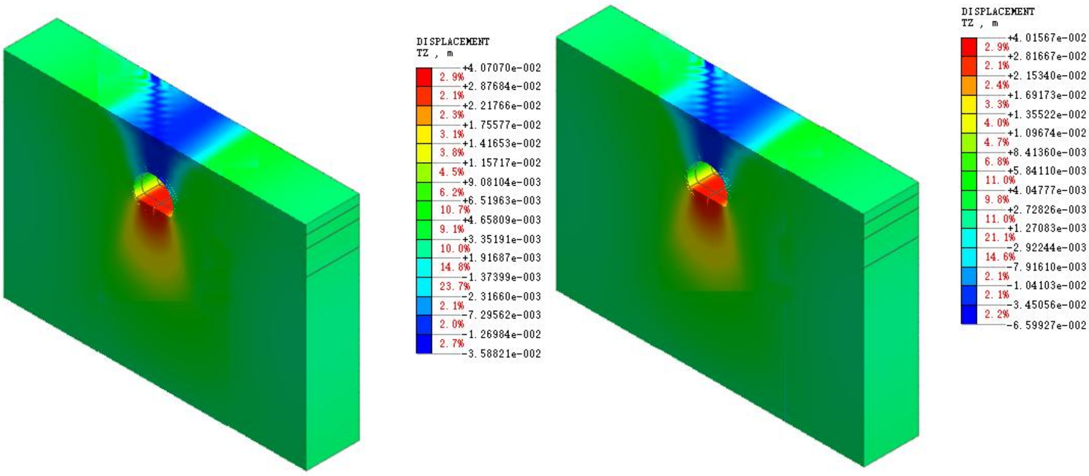


Figure4 Comparison Diagram of Surface Settlement Curves without Vehicle Load and at Different Vehicle Speeds

5.2 Study on the influence of vehicle load on ground subsidence

Keep the optimal driving speed at 20km/h, and change the vehicle static load to 100kN, 200kN and 300kN respectively. Study the impact of vehicle load on ground settlement. Figure 5 shows the three-dimensional settlement displacement nephogram of the model under 200kN and 300kN loads.

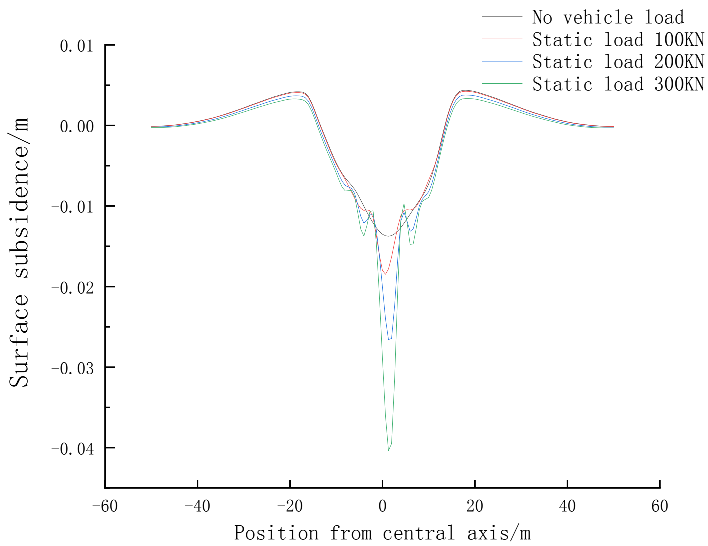
It can be seen from Figure 3 (a) (b) and Figure 5 that the increase of vehicle static load has a significant impact on the soil settlement. Within the range of vehicle load, the soil settlement increases. Under the action of 200kN vehicle load, the range of soil settlement increases, and the maximum settlement value increases by 48% compared with 100kN. The overall settlement under 300kN load is similar to that under 200kN vehicle static load. The maximum settlement value is obtained at the vault, and the settlement value decreases gradually towards the surrounding. At the same time, due to the effect of vehicle load, the settlement influence range continues to increase.At this time, the static load value of the vehicle is large, and the vibration generated in the loading process is also large, so the settlement value fluctuates significantly within the range of vehicle load. The overall maximum settlement value increases from 24.0mm under no load to 24.2mm, 35.9mm and 66.0mm, and the 66.0mm under static load of 300kN far exceeds the limit of construction requirements, which is extremely unfavorable to construction safety.



（a）3D settlement displacement nephogram when vehicle static load is 200kN （b）3D settlement displacement nephogram when vehicle static load is 300kN

Figure5 Three dimensional settlement displacement nephogram under vehicle static load of 200kN and 300kN

Figure 6 shows the comparison diagram of the surface settlement curve when there is no vehicle load and the vehicle static load is 100kN, 200kN and 300kN. With the increase of load, the overall trend of the curve will not be affected. The maximum settlement value will be obtained at the center line of the tunnel, and the settlement value on both sides will gradually decrease. There is a certain amount of uplift at the outside of the tunnel arch shoulder. With the increase of the vehicle static load, the width of the settlement trough of the settlement curve has increased. Because the vehicle load is simplified as a local action caused by the force acting on the node in the numerical simulation process, there is a certain maximum settlement value on both sides of the tunnel centerline when there is vehicle load. The maximum value of surface settlement gradually increases from 13.7 mm without vehicle load to 18.0 mm, 26.3 mm and 39.2 mm, with growth rates of 31.4%, 92.0% and 186.1% respectively. With the increase of vehicle static load, its impact on surface settlement also increases, and the ring ratio increase rate of maximum settlement also increases. Compared with the impact of vehicle speed on surface settlement, surface settlement is more affected by vehicle static load. Therefore, during tunnel construction, the load of vehicles passing on the road above shall be strictly controlled to not exceed 100kN to ensure construction safety and surface settlement within a safe range.



5.3 Study on the influence of vehicle load on ground settlement of different tunnel projects

In actual projects, double tunnel projects are also common. When studying the ground deformation caused by the excavation of double track tunnels, if linear superposition is directly used for analysis only based on the calculation results of single track tunnels, the interaction between double track tunnels is ignored. In order to study the impact of vehicle load on double tunnel project, the optimal vehicle load obtained above is set. The vehicle speed is 20km/h, and the vehicle static load is 100kN. The numerical model of double tunnel project under vehicle load is established as shown in Figure 7. The location of the surface settlement curve is selected as the middle of the width of the model, where the vehicle load acts on the middle of the two tunnels.

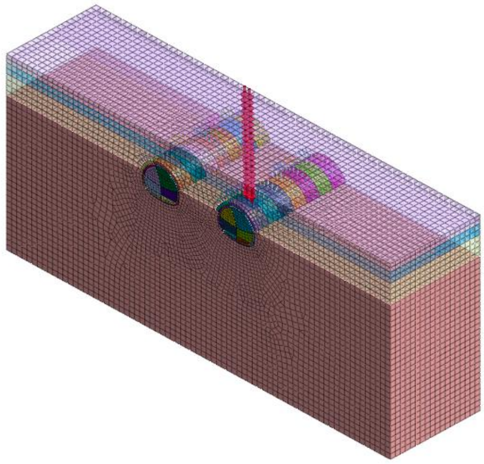
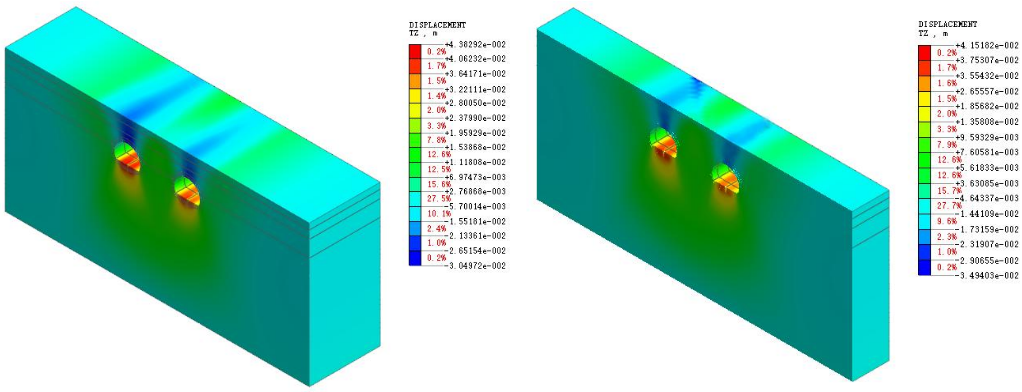


Figure7 Numerical model of double tunnel under vehicle load

Figure 8 shows the three-dimensional settlement displacement nephogram of double tunnel project under the action of vehicle load. On the whole, the settlement displacement nephogram under the action of vehicle load is similar to that without vehicle load. The settlement of the tunnel excavated first on the left is slightly greater than that of the soil above the tunnel on the right. At the intersection of the left tunnel and vehicle load, the soil settlement increases due to the vibration of vehicle load. Compared with the double tunnel project without vehicle load, the maximum settlement value increases by 4.4 mm; Compared with the case of vehicle load acting on a single tunnel project, the maximum settlement value increases by 10.1mm. It can be seen that the impact of vehicle load on ground settlement is more obvious in the double tunnel project.



（a）3D settlement displacement nephogram of double tunnel project without vehicle load	（b）3D settlement displacement nephogram of double tunnel project under vehicle load

Figure8 Three dimensional settlement displacement nephogram of double tunnel project under no vehicle load and vehicle load

Figure9 shows the comparison of the surface settlement curves under the conditions of single and double tunnel projects without vehicle load and vehicle load. It can be seen from the figure that the effect of vehicle load does not change the overall trend of the surface settlement curves. The curves in single tunnel projects are approximately "V" shaped, while those in double tunnel projects are approximately "W" shaped. The maximum surface settlement is above the left tunnel, and there is a certain amount of uplift at the outside of the tunnel arch shoulder. The vehicle load acts on the middle of the double tunnel, which increases the ground settlement in the middle and affects the soil mass within the scope of action. The effect of vehicle load makes the soil above the left tunnel lead to additional settlement of 5.1mm, the maximum settlement value reaches 33.3mm, increased by 22.4%, and expanded the settlement difference between the left and right tunnels, which is adverse to construction safety. Compared with single tunnel project, the maximum settlement value increases from 13.7 mm to 27.2 mm without vehicle load, which is 98.5% higher; Under the action of vehicle load, the maximum settlement value increases from 18.0mm to 33.3mm, an increase of 85%. It can be seen from this that in the double tunnel project, the ground settlement changes significantly increase, and the impact of vehicles on the ground settlement cannot be ignored. Therefore, in the double tunnel project, it is necessary to strictly check whether the vehicles passing by are overloaded, and prohibit vehicles from passing if necessary.

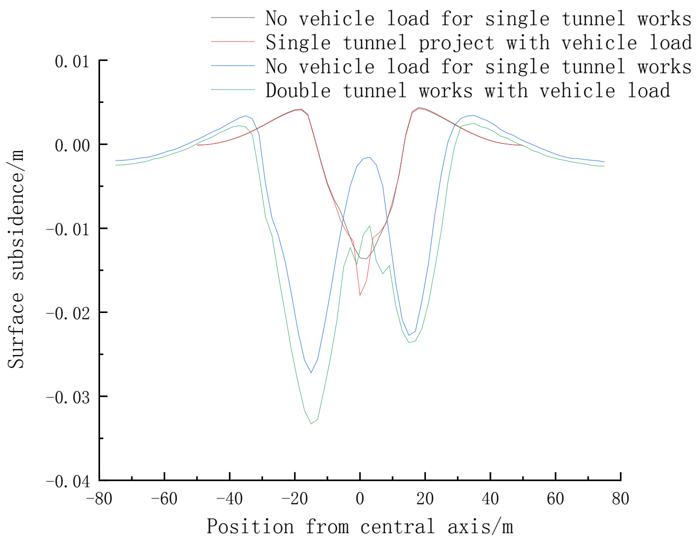


Figure9 Comparison Diagram of Surface Settlement Curves of Single and Double Tunnels without Vehicle Load and Vehicle Load

VI. CONCLUSION

In this paper, relying on an airport tunnel project example, three-dimensional numerical simulation is established using MIDAS GTS NX finite element software to study the impact of vehicle load on ground settlement during construction. The specific conclusions are as follows.

1)In a single tunnel project, with the increase of driving speed and vehicle load, the trend of the surface settlement curve will not be changed. The surface settlement curve will all obtain the maximum settlement value above the tunnel centerline and show a "V" shape. The maximum surface settlement increases with the increase of driving speed. Due to the large traffic demand in the area where the Project is located, in order to ensure normal traffic and meet the needs of construction safety and surface settlement, the driving speed of vehicles passing above shall not exceed 20km/h during tunnel excavation.

2)When the vehicle load increases continuously, the width of the settlement trough of the surface settlement curve increases, and the maximum settlement value at the vault and the maximum settlement value of the surface increase. The greater the static load of vehicles, the greater the impact on the ground settlement, and the more adverse to the construction safety and the surrounding environment. When the static load of vehicle is 100kN, the maximum ground settlement is 18mm, which meets the construction needs. Therefore, during the construction process, the load of passing vehicles shall be strictly controlled to not exceed 100kN.

3) The double tunnel project is more complex than the single tunnel project. The effect of vehicle load does not change the trend of the surface settlement curve, which is still approximately "W" shaped. However, due to the vibration of vehicle load, the surface settlement value at its action location changes greatly. At the same time, the vehicle load makes the soil above the left tunnel produce greater additional settlement, resulting in greater uneven settlement of the soil above the two tunnels; The maximum settlement under load is 85% larger than that of single tunnel project, which is not conducive to construction safety and stability of surrounding structures. Therefore, during the construction of double tunnel project, the traffic on the road above the tunnel shall be strictly restricted or prohibited in combination with the actual conditions and the surrounding environment to ensure safety.

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