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Study on Dynamic Response and Vibration Reduction Characteristics of Rubber Concrete Tunnel Lining

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Abstract: In this paper, the dynamic response characteristics of rubber concrete tunnel lining are studied when the cross clearance of intersecting tunnel is 3 m, 6 m, 9 m and 12 m respectively, the results show that the vertical displacement, vertical acceleration and maximum principal stress of the measuring point increase gradually as the train moves closer to the measuring point, and decrease to zero after reaching the final value, moreover, the vertical displacement, vertical acceleration and maximum principal stress of the vaults of the two tunnels are the largest, and with the increase of the cross-section net distance, the vertical displacement, vertical acceleration and maximum principal stress of the monitoring points at the vault of section a decrease gradually. Taking the A-d test points as an example, the vertical displacement of the corresponding test points of the rubber concrete lining decreases by 0.0125 mm, 0.0074 mm, 0.0054 mm, 0.0040 mm respectively compared with that of the normal concrete lining when the cross clear distances are 3m, 6m, 9m and 12m, the vertical acceleration decreases by 0.074 m/s^2,0.05 m/s^2,0.026 m/s^2,0.018 m/s^2 , respectively, and the maximum principal stress decreases by 4.3 kPa, 2.4 kPa, 1.2 kPa, 0.4 KPA respectively.

Keywords: Rubber concrete; dynamic response; cross clearance; damping characteristics.

1. Introduction

Railway transportation is widely used at home and abroad as a kind of transportation tool with high speed, large transportation capacity, good safety performance and running on time. With the rapid growth of transportation demand, the train gradually to heavy-duty, high-speed development, in some specific conditions, the two railways are bound to overlap. The influence of the vibration load generated by the upper train on the lining structure of underground tunnel is more and more prominent, which seriously affects the safe operation and service life of tunnel.

Throughout the world, the amount of rubber waste is gradually increasing, and in developed countries, it is estimated that waste tyres are produced at a rate of one tyre per person and that 1 billion waste tyres will be produced each year, more than 50% of tyres are discarded without any treatment, seriously hindering the sustainable development of society. A huge amount of waste tyres are difficult to be disposed of in landfills and are not easy to biodegrade. Random accumulation will affect the ecological environment and even lead to uncontrollable fires. Incineration treatment will cause secondary pollution, release a lot of smoke and toxic gases, serious pollution of the atmosphere environment. In view of the difficulty of waste rubber treatment, it is put forward that adding waste rubber into concrete can not only improve the brittleness of concrete and increase the anti-vibration ability of concrete, but also can treat a lot of waste tires, it has become an effective and pollution-free way to digest waste rubber, bringing considerable economic and environmental value.

Foreign experts and scholars have done a series of researches on the functions [1,2] and dynamic properties [3] of rubber concrete, but these researches mostly focus on the basic mechanical properties of rubber concrete In recent years, the research on the vibration reduction characteristics of rubber concrete in rail transit has been carried out in China, and Jin Hao et al have studied the influence of rubber concrete base on rail vibration by using Periodic Fourier method [4] , sun Xiaojing analyzed the vibration reduction effect of rubber concrete monolithic ballast, but did not consider the influence of rubber concrete ballast on driving.

The minimum clear distance of overlapped section is only 2m, and the length of overlapped section is 300m, and the overlapped length between 2-4m is 200m. These bring many technical problems to the design and construction. The domestic and foreign scholars have carried out the train vibration test and finite element numerical simulation for the interval tunnel, but the research on some vibration reduction measures is relatively few. In this paper, the dynamic response characteristics of rubber concrete lining under different cross clearances are studied by using some engineering parameters, and the vibration reduction characteristics of rubber concrete lining are studied by comparing the dynamic response of ordinary concrete lining.

2. Dynamic Analysis Model

2.1. Modeling

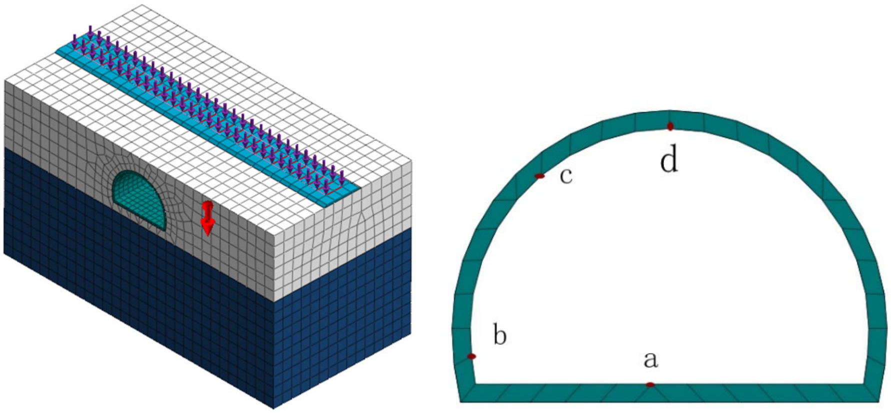
Midas GTS/NX model was used to simplify the details of drainage ditch and cable trench. According to previous studies, it is determined that in order to reduce the influence of boundary effect in numerical simulation, the size of the model should be greater than 5 times the hole diameter, the region of the numerical model with the length × height × thickness = 60m × 37.6 m × 40m (when the cross clearance is 3M) is set as track, ballast layer, four-grade wall rock and three-grade wall rock from top to bottom. The model of type III reinforced concrete sleeper is built over ballasted layer, and the sleeper is simplified as a rectangular structure, its length × width × height = 2.9 m × 0.2 m × 0.21 m, and its spacing is 0.6 m. the sleeper is connected to two steel rails, the bottom of the track is coupled with the ballast layer. The ballast layer is 6.87 m wide and 0.35 m thick, and the slope angle of ballast layer is 30 ° .The thickness of the fourth-order wall rock is 12.6 m, and the third-order wall rock is 25m. In the numerical model, solid elements are used for lining and surrounding rock, and the constitutive relation is elastic for lining and Maurs-Cullen constitutive model for surrounding rock.

2.2. Main design parameters

All materials in the model are isotropic materials, and the influence of joint surface, fault and groundwater are not considered. The physical and mechanical parameters of the numerical model are obtained according to the similarity relation design, the railway track design code, the highway tunnel design code and the related physical and mechanical properties test, as shown in table 1.1. The 3-D Cartesian coordinate system model is constructed, with the x, y and z axes representing the radial, axial and vertical directions of the tunnel respectively. The whole 3-d model consists of 21,624 nodes and 40,735 elements. The numerical models are shown in figure 1.1, Z = 0m (section a) , z = 3.2 m (section B) , Z = 6.4 m (section C) at the distance from the orthogonal point, respectively.

Table 1.1. Numerical model parameters for various structural materials in the underground tunnel

Model structure	The constitutive model	Elastic modulus E(GPa)	Siméon Denis Poisson μ	Angle of internal friction Φ(deg)	Cohesion c(MPa)	Bulk density γ(kN/m3)	Damping ratio
Sleepers	elasticity	30	0.24	-	-	25.0	0.01
Rail	elasticity	210	0.31			78.5	0.03
Ballast layer	elasticity	0.21	0.30	-	-	23.0	0.05
Quaternary surrounding rock	Mohr -Cullen	4.0	0.33	33.0	0.5	21.6	0.05
Tertiary surrounding rock	Mohr -Cullen	8.0	0.28	42.0	1.1	25.4	0.04
Ordinary concrete tunnel	elasticity	31.4	0.32	-	-	24.3	0.02
Rubber concrete tunnel	elasticity	22.7	0.23	-	-	20.0	0.1



(a) Numerical model (b)Tunnel point

Figure 1.1 Numerical model of the underground tunnel crossing

2.3. Train load simulation

The train simulation takes the MugunghwaTrain train as the prototype, and the first 10 continuous axles of the train are selected as the moving load of the train in the simulation. The train speed is 40m/s. The axle spacing and axle load of the train are shown in the table. The forward route of the train along the sleeper is set, and the nodes on the track are selected as the application points of the train load, as shown in the two rows of arrows above the sleeper in Figure 1.1. Through the sleeper, the point load of the train is converted into surface load and transferred to the ballast layer.

Table 1.2 The standard load parameters for the first 10 axles of the Mugunghwa Train model

ID	1	2	3	4	5	6	7	8	9	10
Shaft spacing (m)	0.000	1.854	1.854	8.789	1.854	1.854	4.582	1.854	1.854	8.789
Axle load (kN)	280	280	280	280	280	280	280	280	280	280

3. Analysis of Influence of Distance from Tunnel Arch to Track Top on Dynamic Response of Lining

By controlling the train axle load of 280kN and train speed of 40m/s, the calculation models of rubber concrete and ordinary concrete lining with the cross clear distance (distance from tunnel arch to track top) of 3m, 6m, 9m and 12m are designed, and the vertical displacement, vertical acceleration and maximum principal stress of each measuring point are studied. The dynamic response of rubber concrete lining with the change of cross clear distance is studied, and the corresponding vibration reduction law is compared with that of ordinary concrete tunnel.

3.1. Rubber concrete lining responds to vertical displacement

Under different cross clear distance, the vertical displacement time-history curve of each measuring point has the same trend and only changes the peak value. Fig. 2.1 shows the vertical displacement time-history curve of each measuring point of section A of the rubber concrete lining when the cross clear distance is 6m.

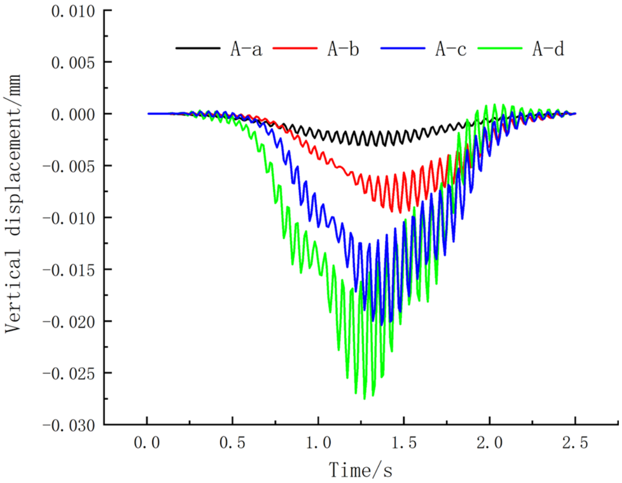


Figure 2.1. A vertical displacement time-history curve of each measuring point

According to the analysis of Fig. 2.1, as the train gradually approaches the measuring point, the vertical displacement of the measuring point gradually increases, and gradually decreases to zero after reaching the maximum value. The time of reaching the maximum value of each measuring point is inconsistent, and the peak value of the arch is the largest, while the bottom plate is the smallest.The peak value of vertical displacement at each measuring point of rubber concrete lining under different cross clearances was counted, as shown in Table 2.1.The figure shows the vertical displacement curves of each measuring point of rubber concrete lining under different cross clearances.

Table 2.1 peak vertical displacement of rubber concrete lining under different cross clearance (10^{-3}mm)

Cross clearance Measuring point	3m	6m	9m	12m
A-a	-3.951	-3.1	-2.681	-2.402
A-b	-13.36	-9.551	-7.767	-6.637
A-c	-31.32	-20.41	-15.1	-12.27
A-d	-45.61	-27.51	-19.51	-15.44
B-a	-3.737	-3.014	-2.635	-2.387
B-b	-11.74	-8.756	-7.285	-6.324
B-c	-21.42	-17.21	-13.63	-11.36
B-d	-34.21	-22.22	-17.07	-14.03
C-a	-3.352	-2.831	-2.546	-2.359
C-b	-8.469	-7.046	-6.251	-5.717
C-c	-12.77	-10.94	-9.537	-8.472
C-d	-16.7	-14.16	-12.44	-11.02

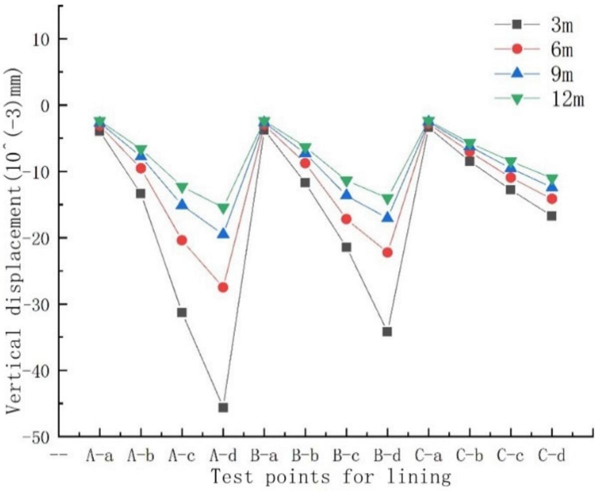


Figure 2.2. Vertical displacement curves at various measuring points under different cross-sectional clearances

The analysis and calculation results show that:When the distance from the tunnel arch to the top of the track is 6m, 9m and 12m, the vertical displacement values of the monitoring point d of the arch of the rubber concrete lining at the section Z=0m are 0.029mm, 0.021mm and 0.016mm, respectively, which are reduced by 39.6%, 57.2% and 66.1% compared with 0.049mm when the cross clearance distance is 3m.In addition, when the cross clear distance increases from 3m to 6m, 6m to 9m and from 9m to 12m, the vertical displacement decreases by 39.6%, 29.1% and 20.8% respectively, indicating that the smaller the distance from tunnel top to track top, the larger the vertical displacement value of the monitoring point at the arch at the crossing point, and the smaller the cross clear distance, the faster the vertical displacement change.

3.2. Vertical acceleration response of rubber concrete lining

The acceleration time history curve of each measuring point has the same trend under different cross clear distance, and only changes the peak value. Fig. 2.3 shows the vertical displacement time history curve of each measuring point of section A of the rubber concrete lining when the cross clear distance is 6m.

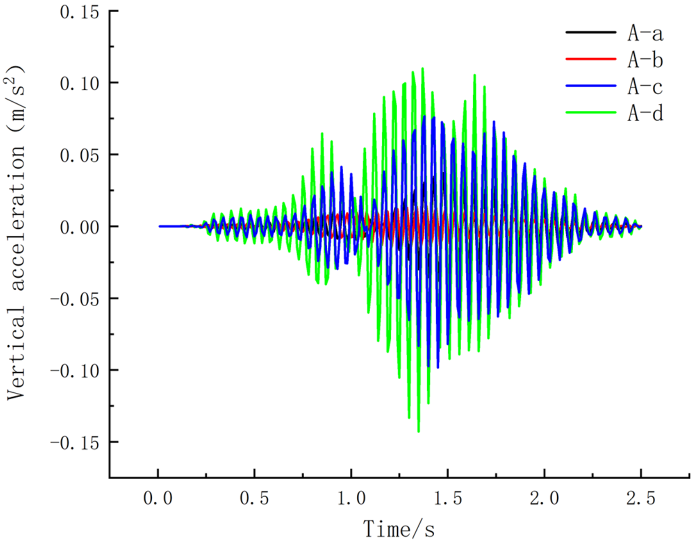


Figure 2.3. A vertical acceleration time-history curve of each measuring point

According to the analysis of FIG. 2.3, as the train gradually approaches the measuring point, the vertical acceleration of the measuring point gradually increases and gradually decreases to zero after reaching the maximum value. The time of reaching the maximum value of each measuring point is inconsistent, and the peak value of the arch is the largest, while the bottom plate is the smallest. The peak value of vertical acceleration at each measuring point of rubber concrete lining under different cross clearances was counted, as shown in Table 2.2.FIG. 2.4 shows the vertical acceleration curves of each measuring point of rubber concrete lining under different cross clearances.

Table 2.2. the peak values of vertical acceleration of each testing point of the rubber concrete lining under different cross clearance (m/s^2)

Cross clearance Measuring point	3m	6m	9m	12m
A-a	-3.129	-1.479	-0.595	-0.6519
A-b	-6.971	-3.795	-2.341	-1.897
A-c	-20.07	-9.833	-5.547	-3.694
A-d	-29.85	-14.27	-7.709	-5.132
B-a	-2.862	-1.388	-0.8017	-0.6456
B-b	-5.864	-3.232	-2.144	-1.741
B-c	-10.95	-8.202	-4.728	-3.169
B-d	21.98	-11.17	-6.268	-4.257
C-a	-2.221	-1.146	-7.563	-0.6225
C-b	-3.874	-2.568	-1.785	-1.417
C-c	-6.892	-4.133	-2.799	-2.121
C-d	-10.19	-6.373	-4.111	-2.99

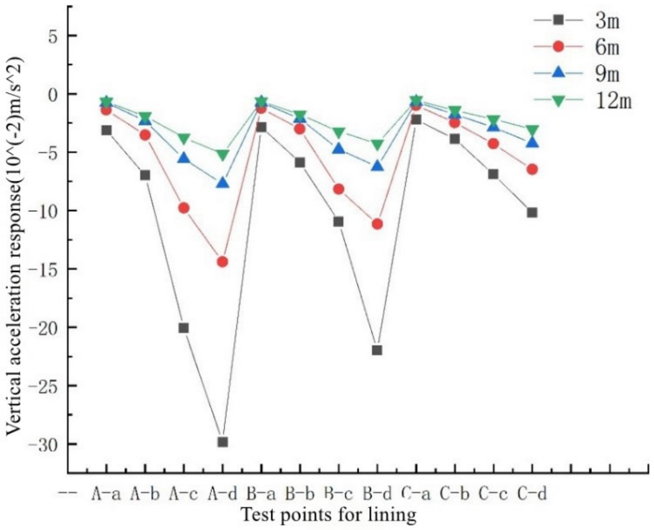


Figure 2.4 Vertical acceleration curves at various measuring points under different cross-sectional clearances.

The analysis and calculation results show that:

When the cross distance of the tunnel is 6m, 9m and 12m, the vertical acceleration of the monitoring point a of the arch roof at the section Z=0m is 0.144m/s2, 0.771m/s2 and 0.515m/s2, respectively, compared with the 0.299m/s2 when the cross distance is 3m.In addition, the vertical acceleration decreases by 51.7%, 74.2% and 82.7%, respectively, when the cross clear distance increases from 3m to 6m, from 6m to 9m and from 9m to 12m, respectively. It shows that the smaller the distance between the tunnel top and the track top, the greater the vertical acceleration of the monitoring point at the arch of section A. The smaller the cross distance is, the faster the vertical acceleration changes.

3.3. Maximum principal stress response of rubber concrete lining

The vertical acceleration time-history curve of each measuring point has the same trend under different cross clear distances, and only changes the peak value. FIG. 2.5 shows the vertical displacement time-history curve of each measuring point of section A of the rubber concrete lining when the cross clear distance is 6m.

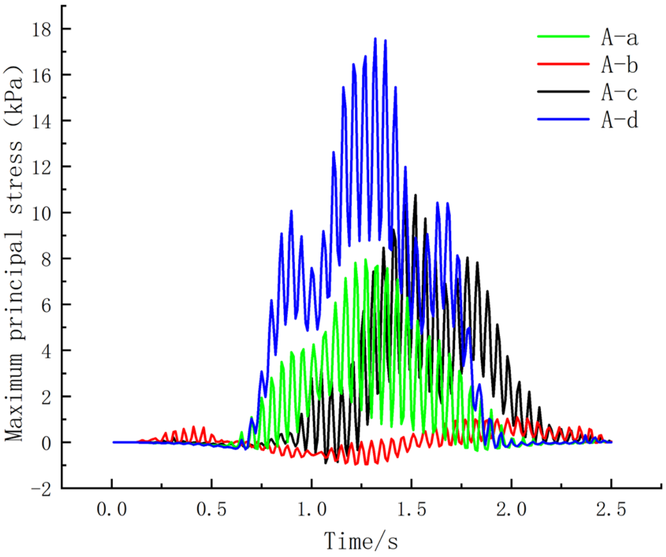


Figure 2.5 A vertical displacement time-history curve of each measuring point

According to the analysis of FIG. 2.5, as the train gradually approaches the measuring point, the vertical displacement of the measuring point gradually increases and gradually decreases to zero after reaching the maximum value. The time for each measuring point to reach the maximum value is inconsistent, and the peak value of the arch is the largest, while the bottom plate is the smallest. The maximum principal stress of the arch, spandrel and bottom plate is positive. For the arch foot of the test point, the maximum principal stress changes from positive to negative as the train gradually approaches, and from positive to positive as the train moves away.

The maximum peak value of principal stress at each measuring point of rubber concrete lining under different cross clearances was counted, as shown in Table 2.3.FIG. 2.6 shows the maximum principal stress curve of each measuring point of rubber concrete lining with different cross clearances.

Table 2.3. the peak value of the maximum principal stress at each testing point of the rubber concrete lining under different cross clearance (kPa)

Cross clearance Measuring point	3m	6m	9m	12m
A-a	8.294	5.963	4.631	3.799
A-b	0.847	0.610	0.504	0.485
A-c	14.911	9.671	5.766	3.082
A-d	20.379	15.126	10.265	6.782
B-a	6.471	4.758	3.878	3.223
B-b	1.152	0.927	0.715	0.685
B-c	5.993	4.038	2.079	1.022
B-d	3.766	4.400	3.523	2.313
C-a	4.026	3.310	2.815	2.441
C-b	0.986	0.831	0.828	0.391
C-c	2.004	1.524	0.960	0.317
C-d	1.090	0.172	0.185	0.124

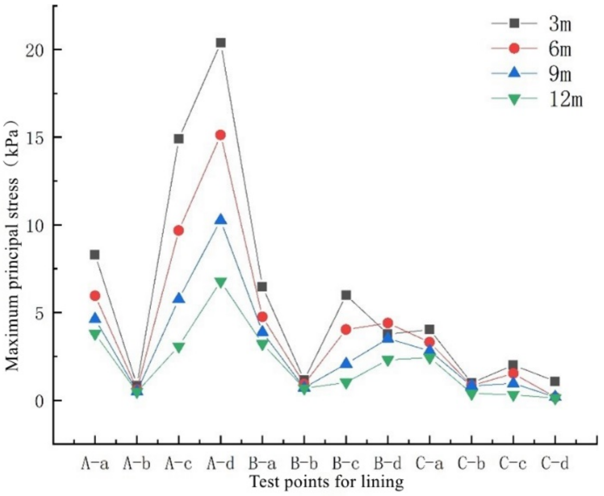


Figure 2.6. Maximum principal stress curves at various measuring points under different cross-sectional clearances

The analysis and calculation results show that: along the longitudinal direction of the tunnel, as the measuring points gradually move away from the vertical cross section, the maximum principal stress at the arch foot has no obvious change, and the other measuring points gradually decrease, among which the maximum principal stress at the arch top has a significant decrease, and the maximum principal stress at the Z=3.2m and Z=6.4m sections is satisfied with the relationship of floor > spinner > vault > arch foot.

The maximum principal stress values at the monitoring point a of the arch roof at the section Z=0m were 15.12kPa, 10.26kPa and 6.78kPa when the clear distance between tunnels was 6m, 9m and 12m, respectively, which decreased by 25.7%, 49.6% and 66.7% compared with 20.38kPa when the clear distance between tunnels was 3m.The results show that the smaller the distance between tunnel arch and track top is, the greater the maximum principal stress is at the arch top of section A.

4. Analysis of Vibration Reduction Characteristics of Rubber Concrete Lining

The calculation model of ordinary concrete under different cross clearances was calculated, and the vertical displacement, vertical acceleration and maximum principal stress peaks of each measuring point were calculated, as shown in Table 3.1, 3.2 and 3.3, respectively.

Table 3.1 The peak values of vertical displacement of common concrete lining at different cross spacing (10^{-3}mm)

Cross clearance Measuring point	3m	6m	9m	12m
A-a	-3.990	-3.288	-2.926	-2.656
A-b	-13.665	-9.633	-7.803	-6.663
A-c	-41.460	-25.719	-19.678	-15.581
A-d	-58.139	-34.910	-24.908	-19.469
B-a	-3.785	-3.229	-2.893	-2.647
B-b	-11.922	-8.825	-7.295	-6.328
B-c	-30.600	-23.451	-17.846	-14.443
B-d	-43.283	-28.945	-22.421	-17.798
C-a	-3.272	-3.120	-2.839	-2.626
C-b	-8.306	-7.109	-6.283	-5.729
C-c	-17.067	-14.366	-12.450	-10.949
C-d	-24.746	-20.002	-16.557	-14.224

Table 3.2 the peak values of vertical acceleration of normal concrete lining at different cross spacing (m/s^2)

Cross clearance Measuring point	3m	6m	9m	12m
A-a	-3.732	-1.657	-1.461	-0.961
A-b	-8.486	-4.295	-3.060	-2.614
A-c	-24.354	-12.953	-7.477	-5.086
A-d	-37.222	-19.434	-10.276	-6.911
B-a	-2.966	-1.411	-0.864	-0.853
B-b	-7.217	-3.671	-2.859	-2.403
B-c	-17.924	-10.852	-6.385	-4.412
B-d	-26.833	-14.893	-8.320	-5.698
C-a	-2.926	-1.089	-0.816	-0.644
C-b	-5.990	-3.093	-2.321	-1.896
C-c	-8.967	-5.981	-3.986	-3.015
C-d	-14.205	-8.838	-5.873	-4.125

Table 3.3 maximum principal stress peak values of ordinary concrete lining at different cross spacing (kPa)

Cross clearance Measuring point	3m	6m	9m	12m
A-a	11.48	7.955	5.947	4.688
A-b	1.566	1.098	0.8805	0.8246
A-c	17.32	10.75	6.121	3.118
A-d	24.69	17.57	11.41	7.2
B-a	8.88	6.292	4.934	3.939
B-b	1.583	1.228	0.9106	0.8382
B-c	8.235	5.346	2.649	1.251
B-d	5.109	5.749	4.427	2.791
C-a	5.399	4.274	3.494	2.907
C-b	1.256	1.017	0.9721	0.4399
C-c	2.628	1.922	1.163	0.3686
C-d	1.646	0.251	0.2606	0.1688

Figure3.1, Figure3.2 and Figure 3.3 are the comparison of vertical displacement, vertical acceleration and maximum principal stress of rubber concrete lining and ordinary concrete lining respectively.

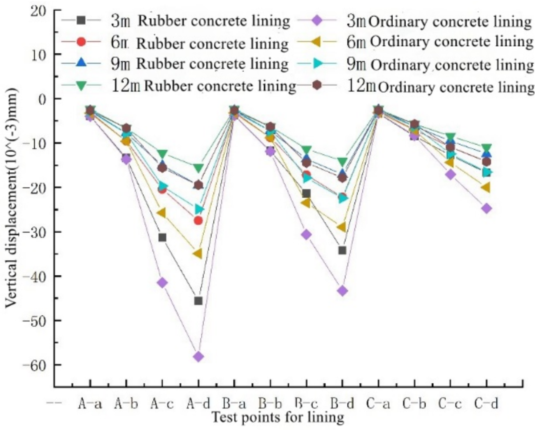


Figure 3.1 Comparison of vertical displacement at various measuring points under different cross-sectional clearances.

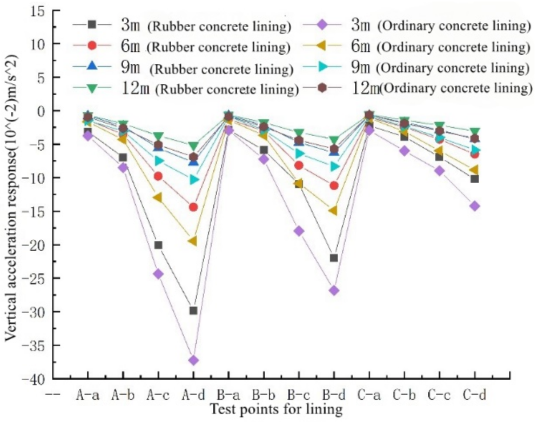


Figure 3.2 Comparison of vertical acceleration at various measuring points under different cross-sectional clearances

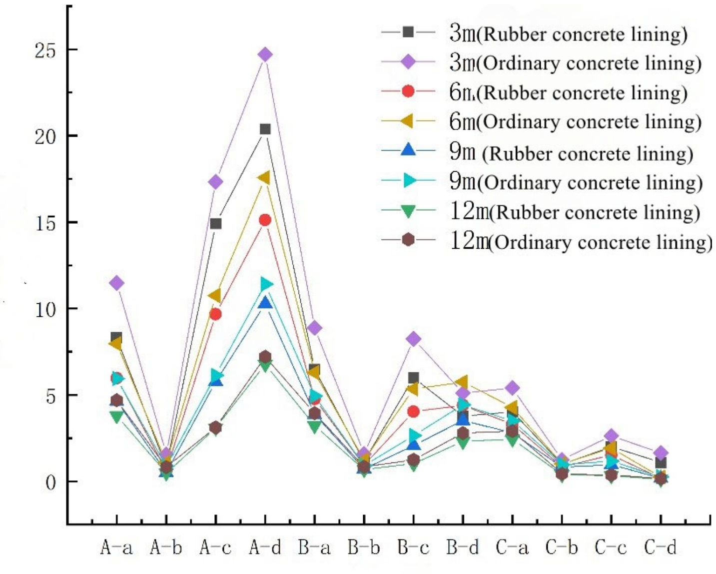


Figure 3.3 Comparison of maximum principal stress at various measuring points under different cross-sectional clearances

As can be seen from the calculation results and the figure: The peak value of vertical displacement at each measuring point of rubber concrete lining is basically reduced compared with that of ordinary concrete under different cross clearances, and the reduction law of each measuring point is inconsistent. The vault and spinner of section A and B decrease greatly. Taking A-D measuring points with significant changes as an example, when the cross clearances are 3m, 6m, 9m and 12m, the vertical displacement of rubber concrete lining is compared with that of ordinary concrete lining. The vertical displacement of rubber concrete lining is reduced by 0.0125mm, 0.0074mm, 0.0054mm and 0.0040mm respectively. The smaller the cross clear distance, the better the vertical displacement attenuation effect.

The peak value of vertical acceleration at each measuring point of rubber concrete lining is basically reduced compared with that of ordinary concrete under different cross clear distance, and the reduction law of each measuring point is inconsistent. On the whole, the measuring point with greater vertical acceleration decreases more significantly. Taking A-d measuring point with the most obvious reduction as an example, when the cross clear distance is 3m, 6m, 9m and 12m, the vertical acceleration of rubber concrete lining is compared with that of ordinary concrete lining. The vertical acceleration of rubber concrete lining decreases by 0.074m/s2, 0.05m/s2, 0.026m/s2 and 0.018m/s2 respectively.

The peak value of the maximum principal stress at each measuring point of rubber concrete lining is basically reduced compared with that of ordinary concrete under different cross clear distance, and the reduction law of each measuring point is inconsistent. The maximum principal stress decreases more obviously at the bottom plate, vault and spinner of section A, among which the A-D measuring point decreases the most when the cross clear distance is 3m, 6m, 9m and 12m.Compared with that of ordinary concrete lining, the maximum principal stress of rubber concrete lining is reduced by 4.3kPa, 2.4kPa, 1.2kPa and 0.4kPa respectively. The research shows that the smaller the cross clear distance, the better the attenuation effect of the maximum principal stress.

5. Conclusion

1.As the train gradually approaches the measuring point, the vertical displacement of the measuring point gradually increases and gradually decreases to zero after reaching the maximum value. The time of reaching the maximum value of each measuring point is inconsistent, and the peak value of the arch is the largest, while the bottom plate is the smallest. When the cross clear distance is 6m, 9m and 12m, the vertical displacement values of A-d are 0.029mm, 0.021mm and 0.016mm, respectively, which are reduced by 39.6%, 57.2% and 66.1%, respectively, compared with 0.049mm when the cross clear distance is 3m.

2.As the train moves closer to the measuring point, the vertical acceleration of the measuring point increases gradually and decreases to zero gradually after reaching the maximum value. The time of reaching the maximum value at each measuring point is inconsistent, and the peak value of the arch is the largest and the bottom is the smallest. When the cross clear distance is 6m, 9m and 12m, the vertical acceleration values of A-a monitoring points are 0.144m/s2, 0.771m/s2 and 0.515m/s2, respectively, which are reduced by 51.7%, 74.2% and 82.7% compared with 0.299m/s2 when the cross clear distance is 3m.

3. As the train gradually approaches the measuring point, the vertical displacement of the measuring point gradually increases, and gradually decreases to zero after reaching the maximum value. The time of reaching the maximum value of each measuring point is inconsistent, and the peak value of the arch is the largest, while the bottom plate is the smallest. The maximum principal stress of the arch, spandrel and bottom plate is positive. For the arch foot of the test point, the maximum principal stress changes from positive to negative as the train gradually approaches, and from positive to positive as the train moves away. When the tunnel cross distance is 6m, 9m and 12m, the maximum A-d principal stress values are 15.12kPa, 10.26kPa and 6.78kPa, respectively, which are reduced by 25.7%, 49.6% and 66.7% compared with 20.38kPa when the tunnel cross distance is 3m.

4. The vertical displacement peak value, vertical acceleration and maximum principal stress at each measuring

point of rubber concrete lining under different cross clear distances are basically reduced compared with that of ordinary concrete, and the reduction law at each measuring point is inconsistent. Taking A-d measuring points with significant changes as an example, when the cross clear distances are 3m, 6m, 9m and 12m, compared with ordinary concrete lining, The vertical displacement of the rubber concrete lining decreases by 0.0125mm, 0.0074mm, 0.0054mm, 0.0040mm, and the vertical acceleration decreases by 0.074m/s2, 0.05m/s2, 0.026m/s2, 0.018m/s2, respectively. The maximum principal stress was reduced by 4.3kPa, 2.4kPa, 1.2kPa and 0.4kPa respectively.

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