

The Influence Evaluation of the Waste Slag Above Tunnel on the Safety of the Structure of the High-Speed Railway Tunnel

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Abstract. A high-speed railway loess tunnel being built is in the Shallow-Buried Section because the construction party violates the design, and the slag discarded at the top of the tunnel is just down-pressing the main line. In order to ensure that the stability of tunnel structure does not affect the safe operation in the later period, a stratum structure model is established based on non-destructive testing and on-site tunnel monitoring measurement. The parameters of surrounding rock are determined by displacement back analysis method, and the influence of waste slag on the safety of tunnel structure is checked by the parameters obtained from back analysis. Through the comparative analysis of the stress of tunnel lining under two working conditions, combined with relevant codes and design documents, it is considered that the slag has a great influence on the stress of tunnel lining structure, but the sectional strength and maximum crack width of eccentrically compressed components of tunnel lining meet the design requirements, and the structure is within the safety range.

Keywords. Tunnel, waste slag, displacement reverse-analysis, structure checking

1. Survey

A high-speed railway tunnel being built is located in the loess hilly area, with a ground elevation of 1906-2095m and a relative height difference of 150-400m. Under the action of water cutting and erosion, gullies are developed, with deep and steep slopes. The maximum excavation width of the tunnel is 14.72m, the excavation height is 12.58m, and the excavation area is 151.6 m². It is a large section loess tunnel. Surface vegetation is not developed. The crossing mileage between the waste slag and the main tunnel is Dk34+135-Dk34+165, which is V grade surrounding rock. The maximum buried depth of the original surface is 84m, and the minimum buried depth is 58m. From the original surface to the top of the waste slag, $H \leq 15\text{m}$. Because the site waste slag is not consistent with the design, the main line is just pressed down by the waste slag. In order to ensure the stability of the tunnel structure, the impact of the waste slag on the tunnel structure is checked and calculated.

Before checking and calculating, the geological radar method [1] and rebound

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method are used to check the quality of tunnel lining in Dk34+100-Dk34+200 section to ensure that the construction quality meets the design requirements [2,3]. It is tested that the spacing, thickness and concrete strength of the second lining reinforcement meet the design requirements, and the second lining is closely connected with the initial support, without defects such as void and cavity behind the second lining.

2. Tunnel Modeling

In the numerical simulation of tunnel engineering, only part of rock mass around the excavation section is usually considered to establish the calculation model, and the boundary constraints with the continuous state of the original rock mass are set on the model. Whether this method is suitable or not will directly determine the accuracy of simulation analysis results. In order to reduce the influence of the boundary effect on the calculation results, the size of the calculation model can be increased, and the part to be analyzed must be in the center of the model, so as to reduce the boundary effect.

According to Saint Venant's principle, the selection of calculation model range [4-6] is determined by the span and height of the tunnel. The left and right boundaries are usually 3-5 times of the span, and the upper and lower boundaries are usually 3-5 times of the height. The rock mass outside the scope of the model taken is not considered to be affected by construction disturbance, that is, the deformation caused by construction can be ignored at these boundaries. According to the section size of the tunnel, the finite element range is determined as 100 m horizontally and 88 m vertically. Considering the minimum buried depth of 58 m, the waste slag is the most unfavorable to the tunnel structure (the boundary value of deep tunnel and shallow tunnel is 35.5m) [7]. Assuming that the original ground line of the tunnel is horizontal, the stacking process of the waste slag is slow, and its direction is orthogonal to the tunnel, which is similar to the weight of the waste slag applied within the original ground range of 15m (according to the most unfavorable factors), and the weight is considered according to the original weight, that is, the uniformly distributed load is applied on the ground surface of 285kN/ m. In the process of simulation, the stress release coefficient of tunnel excavation is 0.5:0.3:0.2.

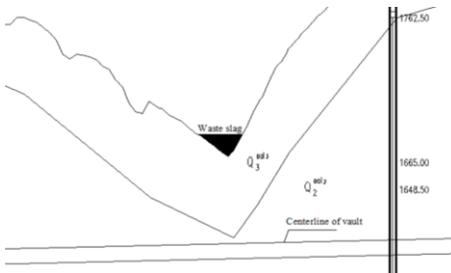


Figure 1. Plane map of intersection

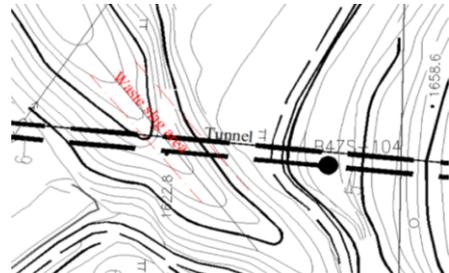


Figure 2. Longitudinal Section of Intersection



Figure 3. On-site waste slag photograph

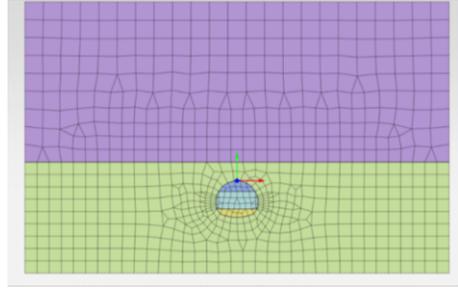


Figure 4. Finite element model

(1) upper boundary

As the tunnel studied in this study is a shallow tunnel, its buried depth has been considered in the model size, so the upper boundary is taken to the ground, without additional conversion of the weight of the overlying rock and soil.

(2) bottom boundary

The boundary condition at the bottom of the tunnel is often simplified to a fixed displacement boundary, that is, the displacement value in the vertical direction is set to zero.

(3) left and right boundaries

Assuming that the rock mass outside the model area is not disturbed by the construction, the corresponding node displacement can be set to zero at the left and right boundaries.

① all materials are considered to be homogeneous, continuous and isotropic.

② the surrounding rock shall be simulated by M-C criterion, the surface element shall be used for the initial support surface, and the beam element shall be used for the secondary lining.

③ the tunnel deformation generally ignores the spatial effect and takes the problem as a general plane strain problem, and adopts a two-dimensional model.

④ the surrounding rock is a shallow loess stratum, in the model, the initial stress field only considers the self weight stress.

⑤ the excavation method of the tunnel is temporary inverted arch method with three steps.

3. Displacement Back Analysis

3.1. Selection of Relevant Parameters

According to the geological exploration data provided on site and related projects, the surrounding rock and support parameters are determined. The first support steel arch is calculated by equivalent mechanical parameter method and added to the elastic modulus of the first support. The results are as follows: $E = E_{\text{initial support}} + E_{\text{section steel}} * A_{\text{shaped steel}} / A_{\text{initial support}}$, $A_{\text{section steel}}$ is the sectional area of steel arch, $A_{\text{initial support}}$ is the equivalent sectional area of each steel frame. The elastic modulus E and internal friction angle θ of Q_2 loess surrounding the lining need to be back analyzed according to the field monitoring data. Specific support parameters see Table 1 and Table 2.

Table 1. Surrounding rock and supporting material parameter table

Material	E / (N/m ²)	μ	γ /(kN/m ³)	c/(kPa)	θ ($^{\circ}$)	Constitutive models
Q ₂ loess	-	0.4	19	50	-	Mohr-Coulomb
Q ₃ loess	0.7×10^9	0.4	18	30	27	Mohr-Coulomb
Initial support	2.8×10^{10}	0.2	25	-	-	Elastic
Second lining	3.25×10^{10}	0.2	25	-	-	Elastic

Table 2. Tunnel support parameters

Material	Position	Specifications
C25 spray concrete	Arch /Wall/ Invert arch	Thickness 35cm
Anchor bolt	Sidewall	1.2m×1.0m, length 3.5m
I25a section steel	Full-circular	Spacing 0.6m
C35 second lining	Full-circular	Invert arch thickness 0.7m, the others 0.6m
Concrete iron	Full-circular	$\Phi 22@20$ cm

3.2. Curve Fitting

Select the tunnel surrounding rock convergence data of section Dk34+135. According to the vertical convergence of the arch crown and the convergence data of the monitoring measurement of the arch waist position (larger value of the left and right arch waist), the curve fitting of the data is carried out to predict the final displacement value [8].

Measured tunnel displacement data:

Vertical convergence value of vault(mm): $D_z = [0\ 6\ 11\ 14\ 18\ 22\ 26\ 31\ 34\ 36\ 38\ 40\ 43\ 45\ 47\ 48\ 49\ 50\ 51\ 52\ 51\ 52\ 51\ 52]$;

Horizontal convergence value of left arch waist (mm): $D_x = [0\ 4\ 10\ 13\ 17\ 20\ 22\ 25\ 26\ 28\ 29\ 28\ 29\ 31\ 30\ 29\ 30\ 30\ 29\ 30\ 30\ 31\ 31\ 31]$;

Time(day): $T = [0.4\ 1.7\ 2.6\ 3.7\ 4.6\ 5.4\ 6.4\ 7.4\ 8.4\ 9.7\ 10.5\ 11.4\ 12.6\ 13.6\ 14.6\ 15.4\ 16.4\ 17.8\ 18.8\ 19.5\ 20.4\ 21.6\ 22.5\ 23.6]$.

According to the principle of least square, Matlab is used to fit the curve according to the monitoring data, and then predict the final displacement value [9].

Vertical displacement fitting curve of arch crown ($r = 0.946$):

$$D_z = 62.2690(1 - e^{-0.0880t}) \quad (1)$$

Fitting curve of horizontal displacement of arch foot ($r = 0.978$):

$$D_x = 36.7967e^{-3.3193/t} \quad (2)$$

At this time, the maximum vertical displacement $d_z = 59.1$ mm, the maximum lateral displacement $d_x = 36.8$ mm. (When the deformation speed of the surrounding rock of the tunnel ≤ 0.0002 m/d, the surrounding rock is stable)

3.3. Inversion Result of Neural Network

According to the mechanical parameters of Q_2 loess elastic modulus E (0.5-1.0GPa) and internal friction angle θ (27-31°), a group maximum value and a group minimum value were selected, and then insert several groups of values in the middle for combination[8,10]. Input each group of data into the established numerical model, record the vertical and horizontal displacement values at the corresponding points with the actual monitoring points. Where $P = [Dz; Dx]$ is the input matrix, $T = [E; \theta]$ is the target matrix, and the final displacement value [11] $P_1 = [59.1 \ 36.8]$.

Using the newgrnn neural network in Matlab toolbox, the date $E = 0.81\text{GPa}$, $\theta = 30^\circ$ are obtained by learning. The data obtained from regression analysis are substituted into the model as surrounding rock parameters, and the maximum vertical displacement Dz is 57.8 mm (the error is 2.5%), the maximum horizontal displacement Dx is 35.2mm (the error is 4.5%).

4. Structural Checking Computation

Tunnel simulation process according to the actual construction excavation method. The parameters of the surrounding rock obtained from the inversion are selected, the three bench excavation method is selected, and the second lining is applied after the excavation. Considering the influence of the overlying slag on the existing tunnel, this paper analyzes two working conditions, and compares the stress of the lining support of the existing tunnel before and after the slag covering, so as to master the stress condition of secondary lining structure.

Analysis condition 1: in the finite element simulation, the tunnel is excavated in three steps , and then the second lining is constructed. The tunnel is analyzed by finite element method without considering the load of waste slag.

Analysis condition 2: in the finite element simulation, after the existing tunnel is completed, the uniform load of 285 kN/m is applied on the surface according to the thickness of the waste slag of 15m to simulate the influence of the waste slag load.

4.1. Deformation and Stress Comparison

(1) Through the comparative analysis of the above two working conditions, it can be seen that the impact of the surface slag load on the existing tunnel.

Table 3. Comparisons of displacements under two conditions (mm)

Working condition	Center of vault Vertical displacement	Left arch waist Horizontal displacement	Center point of invert Vertical displacement
Before loading	-57.8	35.2	0.012
After loading	-58.5	35.4	0.011

It can be seen from Table 3 that the displacement of the second lining of the tunnel changes due to the application of surface load. The horizontal displacement of the left arch waist and the vertical displacement of the inverted arch center point are basically unchanged. The vertical displacement of the arch crown central point increases by 0.7mm, so the influence of the surface load on the displacement of the tunnel structure is small.

(2) Stress comparison of secondary lining structure

Cloud chart of axial force and bending moment of secondary lining before load application:

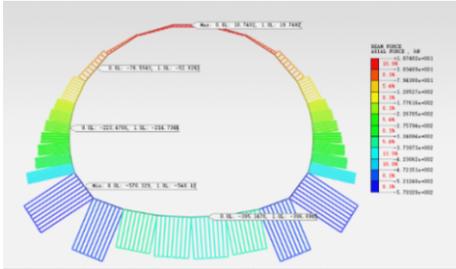


Figure 5. Axis force nephogram before loading

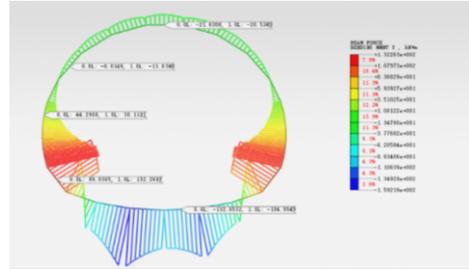


Figure 6. Moment nephogram before loading

Cloud chart of axial force and bending moment of secondary lining after load application:

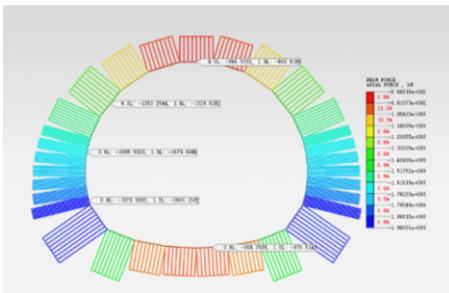


Figure 7. Axis force nephogram after loading

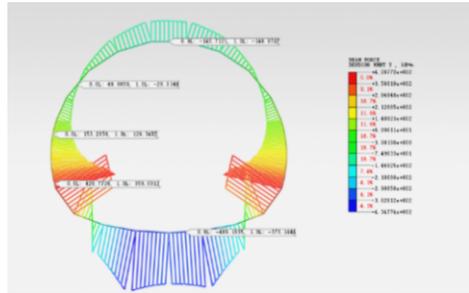


Figure 8. Moment nephogram after loading

It can be seen from the changes of axial force and moment nephogram of the front and rear second lining that the maximum stress is exerted on the side wall of the second lining after the load is applied. The stress conditions of vault, left arch waist, left maximum span, left side wall and inverted arch are shown in the table 4.

4.2. Checking Calculation of Damage Stage

(1) Checking calculation of section strength of eccentric compression member

Refer to Table 4 for the axial force and bending moment after loading, and check and calculate the tunnel lining according to the failure stage method in accordance with code for design of railway tunnel (TB10003-2016). The ultimate bearing capacity of the eccentric compression member is calculated[12,13]. Compared with the actual internal force of the member, the safety factor K of the compressive (or tensile) strength of the section is calculated. Check whether the value required by the code is met. See Table 5 for specific calculation results, and see code for design of railway tunnels (TB10003-2016) for the meanings of corresponding symbols in the above formulas. According to the requirements of the code, the lining safety factor of concrete structure under permanent load and basic variable load shall be greater than 2.0 under compression and 2.4 under tension. According to the above, the section strength meets the design requirements.

Table 4. Comparisons of forces on main parts of two working conditions

Position	Working condition	Vault	Arch waist	Maximum span	Sidewall	Invert arch
Axial force (kN)	Before loading	18.7	76.6	223.5	570.3	395
	After loading	868.9	1315.3	1688.6	1973.9	968.8
Bending moment (kN·m)	Before loading	-21.6	-13.0	44	132	-132
	After loading	-145.7	-28.3	153.3	428.8	-409.2

Table 5. Safety factor checking of secondary lining structures after loading

Position	Axial force (kN)	Bending moment (kN·m)	Lining thickness (m)	Area of reinforcement (cm ²)	Eccentricity	Safety factor	The requirements
Vault	868.9	-145.7	0.60	1900.7	Small eccentricity	12.4	meet
Arch waist	1315.3	-28.3	0.60	1900.7	Small eccentricity	12.6	meet
Maximum span	1688.6	153.3	0.60	1900.7	Small eccentricity	7.7	meet
Sidewall	1973.9	428.8	0.60	1900.7	Large eccentricity	3.4	meet
Invert arch	968.8	-409.2	0.70	1900.7	Large eccentricity	2.9	meet

(2) Checking calculation of maximum crack width of eccentric compression member

According to 8.5.18 of code for design of railway tunnel (TB10003-2016), when $e_0 \leq 0.55h_0$, the crack width may not be checked. Only the inverted arch $e_0 = 0.42\text{m} > 0.55h_0$, the maximum crack width needs to be checked. According to the above formula, the final result is: $w_{max} = 0.15\text{mm}$, which meets the requirements of article 8.5.17 of code for design of railway tunnel (TB10003-2016) that the calculated width limit of surface crack shall not be greater than 0.2mm.

5. Conclusions and Suggestions

Through the comparative analysis of the stress on the tunnel lining under two working conditions, combined with the code for design of railway tunnel (TB10003-2016) and relevant design documents, it is considered that the slag has a great influence on the stress on the secondary lining structure of the tunnel, but the stress on the secondary lining after loading is checked according to the damage stage, and the section strength and the maximum crack width of the eccentric compression component of the secondary lining of the tunnel meet the design requirements. It is considered that the structure is in the safe range.

(1) The stratum structure method is adopted in this calculation, and the value of soil mechanics parameters is obtained through inversion. Due to the deviation between

the inversion results and the actual rock mass, there is a little deviation between the calculated results and the actual engineering stress.

(2) The deformation observation in and at the top of the tunnel shall be strengthened on site. Further strengthen the drainage works to dredge the waste slag and its surrounding areas, so as to prevent the silting area to weaken the physical and mechanical properties of the soil.

(3) Although the internal force value of the control section of the inverted arch meets the requirements of the specification, it is close to the control value of the specification. In case of special circumstances, relevant units shall consider taking other measures according to the calculation results.

(4) The checking calculation must be done after the fact of engineering construction. If the stress or deformation of the check structure is too large, it will have to remove the waste slag and waste a lot of manpower and material resources. The waste slag will have to be removed and a lot of manpower and material resources will be wasted. It is the best policy to follow the design and construction strictly in the construction process.

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