Optimization Design of Tunnel Construction Scheme based on Orthogonal Numerical Simulation Test

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ABSTRACT

This paper adopted orthogonal test method to develop a design methodology for a railway tunnel engineering. This paper mainly focuses on the influences of the deformation in the process of tunnel’s dynamic construction by the following factors: the elastic modulus of advanced support, primary support, excavation footage and release rate of stress. Every factor was investigated on three levels and 9 types of construction were analyzed using orthogonal design methodology. The stratum deformation during dynamic construction of shallow buried tunnel segment was simulated based on the FLAC 3D software. Finally, the range analysis method was utilized to provide an optimal solution of the tunnel’s construction. The results showed that the main construction influence factors of the shallow buried segment of the tunnel is the elastic modulus of advanced support and excavation footage, which means the elastic modulus of primary support and release rate of stress are the secondary influence factors. The optimal construction solution is proposed that includes the elastic modulus of advanced support of 3.2Gpa, the elastic modulus of primary support of 8Gpa, excavation footage of 0.8m, and release rate of stress of step50. The results of this paper could have a certain reference value to some similar engineering’ construction and the study of the deformation during construction in the future.

KEYWORDS: railway tunnel; shallow buried segment; stratum deformation; FLAC 3D; Orthogonal design
1 INTRODUCTION

Tunnel as an underground cross-over engineering structure, has many advantages that other structures cannot match. In recent years, it has been increasing in total mileage. However, the tunnel’s construction will inevitably cause disturbance in the surrounding environment, leading to the deformation of strata, which will influence and even endanger the tunnel’s structure itself and the safety and normal service of surrounding buildings, even resulting in engineering accidents as shown by Hagerty and Ullrich (2010) and Kontogianni et al. (2004). Liu and Sun (2014) analyzed 74 accidents during mountain tunnel’s construction occurred in 2004-2012, among which the proportion of collapsed accidents is high, accounting for 50% of the total accidents. The death toll from the collapse is also the highest, accounting for 43.91%. Yue et al. (2007) carried out statistics on the collapse height and magnitude of more than 50 tunnels, and analyzed the main factors that affected the collapse of the tunnel. Therefore, in order to ensure the safety of the tunnel projects and make sure that the surrounding buildings’ security, it is necessary to deeply research the law of strata deformation in the process of construction and adopt reasonable construction schemes for the tunnels, especially the shallow buried tunnels.

This article based on a railway tunnel engineering, using orthogonal test method for schemes design, and molding the stratum deformation in the process of dynamic construction of the shallow buried segment D2K282+950~D2K283+950 of the tunnel. The influence of elastic modulus of advanced support and primary support, excavation footage and release rate of stress on the deformation in the process of tunnel’s dynamic construction were analyzed, which offers the optimal construction solution for reference to the tunnel.

2 PROJECT PROFILE

The entrance mileage of the tunnel is D2K282+750, and the export mileage is D2K291+423, and the maximum depth of the tunnel is about 480m. The total length is 8673m. The length of the shallow buried segment D2K282+950~D2K283+200 is 15~30m, the surface of which is distributed with mountain trenches, and with thick weathered layer. In addition, the shallow buried segment is located in the syncline core with crushing rock mass and surrounding rock of poor stability, which provides favorable places for groundwater’s enrichment, easily resulting in Water inrush and land slide and other geological disasters during construction.

3 ORTHOGONAL EXPERIMENTAL DESIGN

Orthogonal experimental design is a kind of scientific research method using a set of available normalized tables named orthogonal table to arrange multiple factors and multiple levels tests, and then analyze the tests results so as to identify the optimal experiment scheme. The orthogonal experimental design can greatly reduce the number of test times without affecting the performance indexes of the proposed factors, and its general design processes are as follows: (1) determine the test factors and levels; (2) select the proper orthogonal table; (3) list the test plans and results; (4) analyze the results of the orthogonal test, including the extreme difference analysis and variance analysis; (5) determine the optimal or better
combination of factors. Using orthogonal experimental design, the following conclusions can be drawn as shown by Qi (2006): ① the relationship between factors and indicators; ② The primary and secondary factors; ③ The better production conditions or technological conditions; ④ How to conduct further tests.

3.1 Factors and Levels

Many factors affect the deformation of stratum, including tunnel’s buried depth, section size, construction measures, in-situ stress and groundwater, etc. Considering the purpose of this article is to provide the optimal construction solution, therefore, taking the key influence factors of the orthogonal test respectively the elastic modulus of advanced support and primary support, excavation footage and release rate of stress, and each factor takes 3 levels, shown in Table 1. Considering the realistic conditions of this research, we will not take into account the possible interaction effects between factors, and consider that each factor is independent.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Levels</th>
<th>A elastic modulus of advanced support (GPa)</th>
<th>B elastic modulus of primary support (GPa)</th>
<th>C excavation footage (m)</th>
<th>D release rate of stress (step)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>0.8</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.6</td>
<td>22</td>
<td>1</td>
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<tr>
<td></td>
<td>3</td>
<td>3.2</td>
<td>36</td>
<td>1.2</td>
<td>200</td>
</tr>
</tbody>
</table>

3.2 Orthogonal table and test schemes

The orthogonal experiment design with 4 factors and 3 levels selects orthogonal table L_{9}(3^4), and put of all the factors and levels shown in the table 1 into standardization orthogonal table. After that, 9 kinds of working conditions used for stratum deformation research in the process of tunnel’s dynamic construction can be determined, as shown in Table 2.

<table>
<thead>
<tr>
<th>column</th>
<th>A 1</th>
<th>B 2</th>
<th>C 3</th>
<th>D 4</th>
<th>Maximum vault sinks (mm)</th>
<th>Maximum surface subsidence (mm)</th>
<th>Maximum arching (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>0</td>
<td>8</td>
<td>0.8</td>
<td>50</td>
<td>46.7</td>
<td>12.3</td>
<td>126.3</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>22</td>
<td>1</td>
<td>100</td>
<td>62.3</td>
<td>16.3</td>
<td>154.3</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>36</td>
<td>1.2</td>
<td>200</td>
<td>67.6</td>
<td>21.6</td>
<td>141.4</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>8</td>
<td>1</td>
<td>200</td>
<td>27.4</td>
<td>7.4</td>
<td>132.3</td>
</tr>
<tr>
<td>5</td>
<td>1.6</td>
<td>22</td>
<td>1.2</td>
<td>50</td>
<td>25.3</td>
<td>5.2</td>
<td>127.2</td>
</tr>
<tr>
<td>6</td>
<td>1.6</td>
<td>36</td>
<td>0.8</td>
<td>100</td>
<td>11.8</td>
<td>4.1</td>
<td>110.7</td>
</tr>
<tr>
<td>7</td>
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<td>8</td>
<td>1.2</td>
<td>100</td>
<td>29.4</td>
<td>9.1</td>
<td>139.2</td>
</tr>
<tr>
<td>8</td>
<td>3.2</td>
<td>22</td>
<td>0.8</td>
<td>200</td>
<td>15.3</td>
<td>1.4</td>
<td>112.9</td>
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<tr>
<td>9</td>
<td>3.2</td>
<td>36</td>
<td>1</td>
<td>50</td>
<td>19.0</td>
<td>0.4</td>
<td>129.8</td>
</tr>
</tbody>
</table>
4 NUMERICAL SIMULATION

4.1 Fundamental Assumptions

Due to the physical and mechanical complexity of surrounding rock and the unpredictability of engineering’s characteristics, accurately simulating the excavation of surrounding rock and supporting system completely is impossible. So in this article, based on finite difference software FLAC3D, only main factors were taken into account so as to simplify the model and the simulation process. The numerical simulation assumptions of the article are as follows partially shown by Shi (2014) and Zhu (2011):

1. The tunnel is excavated by CRD method, and the rock mass is excavated out at the same time to complete the initial support, without considering the non-linearity of the rock mass.

2. When the initial stress of the rock mass is calculated, the tectonic stress is ignored, and only the gravity stress is considered.

3. The surrounding rock and the advance support area adopt the entity unit, and the constitutive model adopts the ideal elastoplastic model Mohr-Coulomb. The shell element is adopted in the simulation of initial support of steel arch and shotcrete.

4. For the supporting effect of anchors and steel arch, equivalently simulated by raising the mechanical parameters of surrounding rock in the form of wall rock circle. The calculation method is as follows:

\[ E = E_0 + \frac{S_c E_c}{S_g} \]

In the formula, \( E \) - elastic modulus of concrete after reduction; \( E_0 \) - elastic modulus of the original concrete without conversion; \( S_c \) - sectional area of concrete; \( E_c \) - elastic modulus of steel; \( S_g \) - sectional area of steel arch.

4.2 Establishment of Model

The section of this model is horseshoe shape, and considering that the tunnel is a single-hole tunnel with two-lane of which the distance between each other is 4.6m, the transverse diameter of the tunnel fetches value 14m and the vertical diameter fetches 12m. The width of the model is 3 times of the diameter in width, taking 43m, and then plus the transverse diameter itself, so the width of the model is taken 100m. Downwards, the size of the model is three times higher than the vertical diameter, taking 38m. Because the section of D2K282+950~D2K283+200 is shallow buried, and the surface of which is distributed with mountain trenches, therefore, upwards the size is taken up to the surface, 20m. So in depth the model is calculated in a range of 70m. In the simulation process, only segment D2K283+085~D2K283+115 is used as the study object of which the middle mileage is D2K283+100, the longitudinal length of which is 30m. So the 3D size of the model is 100m×30m×70m. In x-axis, the boundary surface x=50.0 and x=-50.0 are fixed. In y-axis, the boundary surface y=0 and y=30 are fixed. In z-axis, the boundary surface z=-43.0 is fixed, and the other z direction is extended to the surface. The calculation model is shown in figure 1.
Material's physical and mechanical parameters of the model is shown in table 3.

### Table 3 Material Physical and Mechanical Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Density (kg/m³)</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson ratio v</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Cohesion (MPa)</th>
<th>Internal friction angle Ψ</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>surrounding rocks</td>
<td>2000</td>
<td>0.0435</td>
<td>0.3</td>
<td>0.0363</td>
<td>0.0167</td>
<td>0.16</td>
<td>27</td>
<td>0.1</td>
</tr>
<tr>
<td>advanced support</td>
<td>2200</td>
<td>/</td>
<td>0.3</td>
<td>/</td>
<td>/</td>
<td>0.2</td>
<td>30</td>
<td>/</td>
</tr>
<tr>
<td>primary support</td>
<td>2400</td>
<td>/</td>
<td>0.24</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

4.3 Calculation Process

Firstly, the initial stress field is calculated, and the surrounding rocks material parameters and constitutive relation are given to the established stratigraphic model, and then the mechanical calculation is carried out. Because what we need is only the displacement’s change in the process of excavation, so before excavating, all the grid node’s displacement are reset, and then simulating according to the working condition of the actual construction of the tunnel. The excavation method adopts CRD method, and the effects of tunnel entrance shed and advanced small pipes are achieved by improving the physical and mechanical parameters of surrounding rocks in advanced support area. Each excavation cycle, in turn, upper left, lower left, upper right, lower right and timely support. Because the surrounding rocks don’t have the ability of self-stabilization, so assuming once excavation is completed, the primary support is completed at the same time, without considering time effect. The primary support of shotcrete-bolting-mesh combined with steel arch is simulated by shell element, and after that, setting a certain stress release steps. Then remove temporary inverted arches and the middle partition, and running the next excavation cycle. After 10 cycles, the tunnel model is dug through, and then set sufficient stress release until the system balances. Due to the secondary lining is 30m away from the tunnel face, so it's not being considered in this modeling, which can be used as emergency capacity. A set of monitoring points are set every 5m along the longitude of the tunnel to monitor the surface subsidence along the longitude, the settlement of the arch crown and the uplift of the arch bottom.

5 RESULTS ANALYSIS

Based on the 9 kinds of construction conditions in table 2, the calculation results of
maximum settlement of the arch crown, maximum surface subsidence and maximum uplift of the arch bottom are shown in table 2 respectively. In fact, for the orthogonal experiment design with 4 factors and 3 levels, there are 81 kinds of experiment schemes totally, but based on the orthogonal experiment design method, only 9 kinds of schemes were selected as the research objects, and the optimal scheme may be in the 9 schemes or not. So it is necessary to do further analysis and calculation to determine the optimal scheme which will be able to be the reference for the design and construction of primary support and advanced support in actual engineering.

According to the method of range analysis, at first, all the test results of each level under each factor were summed up, as follows shown by Xu et al. (2002):

Factor A:
Maximum surface subsidence:
\[ K_1 = 12.3 + 16.3 + 21.6 = 50.2; \quad K_2 = 7.4 + 5.2 + 1.4 = 16.7; \quad K_3 = 9.1 + 1.4 + 0.4 = 10.9 \]
Maximum settlement of the arch crown:
\[ K_1 = 46.7 + 62.3 + 67.6 = 176.6; \quad K_2 = 27.4 + 25.3 + 11.8 = 64.5; \quad K_3 = 29.4 + 15.3 + 19.0 = 63.7 \]
Maximum uplift of the arch bottom:
\[ K_1 = 126.3 + 154.3 + 141.4 = 422; \quad K_2 = 132.3 + 127.2 + 110.7 = 370.2; \quad K_3 = 139.2 + 112.9 + 129.8 = 381.9 \]

Similarly, the calculation results of factors B, C and D are shown in table 3.

For expressing intuitively, then calculating the arithmetic mean of each result above separately, as follows:

Factor A:
Maximum surface subsidence:
\[ \bar{K}_1 = K_1/3 = 16.7; \quad \bar{K}_2 = K_2/3 = 5.6; \quad \bar{K}_3 = K_3/3 = 3.6 \]
Maximum settlement of the arch crown:
\[ \bar{K}_1 = K_1/3 = 58.9; \quad \bar{K}_2 = K_2/3 = 21.5; \quad \bar{K}_3 = K_3/3 = 21.2 \]
Maximum uplift of the arch bottom:
\[ \bar{K}_1 = K_1/3 = 140.7; \quad \bar{K}_2 = K_2/3 = 123.4; \quad \bar{K}_3 = K_3/3 = 127.3 \]

Similarly, the calculation results of factors B, C and D are shown in table 3.

Calculating the range value \( R \) of each factor, namely the maximum \( \bar{K} \) value minus the minimum \( \bar{K} \) value of each factor, as follows.

Factor A:
Maximum surface subsidence: \( R_1 = 13.1 \); Maximum settlement of the arch crown: \( R_2 = 37.7 \); Maximum uplift of the arch bottom: \( R_3 = 17.3 \).

Similarly, the calculation results of factors B, C and D are shown in table 3.

<table>
<thead>
<tr>
<th>Calculated items</th>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>50.2</td>
<td>28.8</td>
<td>17.8</td>
<td>17.9</td>
</tr>
<tr>
<td>K2</td>
<td>16.7</td>
<td>22.9</td>
<td>24.1</td>
<td>29.5</td>
</tr>
<tr>
<td>K3</td>
<td>10.9</td>
<td>26.1</td>
<td>35.9</td>
<td>30.4</td>
</tr>
<tr>
<td>K1/3</td>
<td>16.7</td>
<td>9.6</td>
<td>5.9</td>
<td>6.0</td>
</tr>
<tr>
<td>K2/3</td>
<td>5.6</td>
<td>7.6</td>
<td>8.0</td>
<td>9.8</td>
</tr>
<tr>
<td>K3/3</td>
<td>3.6</td>
<td>8.7</td>
<td>12.0</td>
<td>10.1</td>
</tr>
<tr>
<td>R1</td>
<td>13.1</td>
<td>2</td>
<td>6.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>
According to the principle of range analysis, \( K_1, K_2 \) and \( K_3 \) reflect the influence of each level under each factor on the indexes of evaluation, and the range value \( R \) reflects the influence of each level’s change under each factor on the indexes of evaluation, namely the larger the range value, the more important of the factor. Therefore, conclusions can be drawn from the above table as follows:

(1) When index of evaluation is the maximum surface subsidence, the primary factor is the elasticity modulus of advanced support. The ranking of all factors’ affecting degree is respectively elastic modulus of advanced support, excavation footage, stress release rate and elastic modulus of primary support.

According to calculation of \( K_1, K_2, K_3 \), in fact, the difference of \( K_1, K_2, K_3 \) in each factor’s column only reflects the factor’s influence on index of evaluation caused by the change of the same factor’s level, and not being affected by other factors’ level. So the optimal scheme is the combination of the best level of each factor, namely the elastic modulus of advanced support takes 3.2Gpa, and the primary support takes 22Gpa, and the excavation footage takes 0.8 m, and the stress release rate takes step50.

(2) When index of evaluation is the maximum settlement of the arch crown, the ranking of all factors’ affecting degree is respectively elastic modulus of advanced support, excavation footage, stress release rate and elastic modulus of primary support. The optimal scheme is that the elastic modulus of advanced support takes 3.2Gpa, and the primary support takes 36Gpa, and the excavation footage takes 0.8 m, and the stress release rate takes step50.

(3) When index of evaluation is the maximum uplift of the arch bottom, the ranking of all factors’ affecting degree is respectively excavation footage, elastic modulus of advanced support, stress release rate and elastic modulus of primary support. The optimal scheme is that the elastic modulus of advanced support takes 1.6Gpa, and the primary support takes 36Gpa, and the excavation footage takes 0.8 m, and the stress release rate takes step50.

The above results show that the main construction factors of shallow buried segment of the tunnel is the elasticity modulus of advanced support and excavation footage, and the elasticity modulus of primary support and stress release rate are the secondary factors. In order to optimally control the above three indexes of evaluation at the same time, now optimize the construction scheme further. Considering the elasticity modulus of advanced support first.
support is the main factor for maximum surface subsidence and maximum settlement of the arch crown, so in order to control the two indexes, take the elasticity modulus of advanced support 3.2Gpa. Considering the excavation footage is the main factors for maximum uplift of arch bottom, so in order to minimize this index, take the excavation footage 0.8m. The range analysis shows that the elastic modulus of primary support is the least important factor for the three indexes, so in order to minimize the construction cost, take the elasticity modulus of primary support 8Gpa. In addition, based on the optimal schemes mentioned in above (1), (2), (3), take the stress release rate step50. So the final optimal scheme is proposed that includes the elastic modulus of advanced support of 3.2Gpa, the elastic modulus of primary support of 8Gpa, excavation footage of 0.8m, and release rate of stress of step50.

Although there are some deficiencies in the above research and analysis, for example, only three levels are considered for each factor and didn’t give full consideration to complex factors in actual engineering, such as cost, construction period and construction complexity and so on, the results of this article still provide valuable reference for the value of levels of the four construction factors, and can be the reference for the tunnel’s construction and some similar shallow buried tunnel engineering.

6 CONCLUSIONS

1. The main construction factors of shallow buried segment of the tunnel is the elasticity modulus of advanced support and excavation footage, and the elasticity modulus of primary support and stress release rate are the secondary factors.

2. The final optimal scheme is proposed that includes the elastic modulus of advanced support of 3.2Gpa, the elastic modulus of primary support of 8Gpa, excavation footage of 0.8m, and release rate of stress of step50.

REFERENCES


