IJE TRANSACTIONS B: Applications Vol. 32, No. 11, (November 2019) 1570-1576

International Journal of Engineering

Journal Homepage: www.ije.ir

Multi-factorial Analysis on Vault Stability of an Unsymmetrically Loaded Tunnel Using Response Surface Method

D. Zhang*[a,b], Z. Zhang[a,c], T. Cheng[a], X. Zhao[d]

[a] *School of Civil Engineering and Architecture, Hubei Polytechnic University, Huangshi, China*
[b] *Department of Civil and Environmental Engineering, National University of Singapore, Singapore*
[c] *School of highway engineering, Chang'an University, Xi'an, China*
[d] *School of Civil Engineering and Architecture, East China Jiaotong University, Nanchang, China*

PAPER INFO

Paper history:
Received 17 August 2019
Received in revised form 29 August 2019
Accepted 12 September 2019

Keywords:
Response Surface Method
Annular Excavation
Vault Settlement
Unsymmetrically Loaded Tunnel

ABSTRACT

This study investigated the vault settlement characteristics of an unsymmetrically loaded tunnel which was excavated by annular excavation via core rock support method. Response surface methodology (RSM) was employed to design the experiments, evaluate the results with the purpose of optimizing the value of design parameters for reducing the vault settlement. The parameters such as horizontal distance, step length, tunneling depth, width of core rock, strength of surrounding rocks and support strength were firstly examined, and a second-order polynomial regression equation was then derived to predict the responses of vault settlement. The percentage contribution, validity of model and effects of different parameters as well as their interactions were assessed by analysis of variance (ANOVA). In the order from high to low effect, these parameters are strength of surrounding rocks, support strength, horizontal distance, width of core rock, tunneling depth, and step length. The results indicated that the influence of uncontrollable factors (i.e. strength of surrounding rocks, tunneling depth, and horizontal distance) on the vault settlement can be reduced through the adjustment of controllable factors (i.e. Width of core rock, step length, and support strength). Moreover, the proposed method in this paper was validated with results of field test measurement and simulation calculation which verified its feasibility.

***doi**: 10.5829/ije.2019.32.11b.08*

1. INTRODUCTION

As a common problem in tunnel construction, the unsymmetrical loading is often inevitable especially at tunnel entrances, mountain sides and valley areas. It is a research topic involving the stability of tunnel vault which is of great interest. To solve the problem caused by unsymmetrical loading [1], many theoretical studies have been conducted concerning the mechanical features of surrounding rocks and tunnel structures [2-6]. Former studies rarely adopt the combination of traditional methods with mathematical statistics (i.e. response surface methodology). The study on the multi-factorial analysis on the stability of unsymmetrically loaded tunnel is very limited. The tunnel stability is one of the most important research topics in tunnel engineering which has been widely studied [7-10]. These studies are beneficial to the tunnel engineers and have become the primary reference for the unsymmetrical loading design for tunnels in many countries. The construction factors, including horizontal distance, step length, tunneling depth, width of core rock, support strength, etc., were not considered as interaction influence on stability of unsymmetrically loaded tunnel excavated by the annular excavation with core rock support method.

Above all, those research only focused on the influence of a single factor on the tunnel stability, which does not consider the interaction among multi-factors. The research concerning the multi-factorial analysis on the vault stability of unsymmetrically loaded tunnels, especially for the tunnel excavated using annular excavation with core rock support method, is scarce. Therefore, it is important to study the effects of various factors on the tunnel vault stability, and analyze the

*Corresponding Author Email: *ericzdb@foxmail.com* (D. Zhang)

Please cite this article as: D. Zhang, Z. Zhang, T. Cheng, X. Zhao, Multi-factorial Analysis on Vault Stability of an Unsymmetrically Loaded Tunnel Using Response Surface Method, International Journal of Engineering (IJE), IJE TRANSACTIONS B: Applications Vol. 32, No. 11, (November 2019) 1570-1576

internal reasons for controlling the tunnel vault settlement.

2. EXPERIMENT PREPARATION AND DESIGN

2. 1. Numerical Model The numerical analysis is performed using the commercial software FLAC3D. The tunnel in this model has a height of 9 m and a width of 12 m. In order to minimize the boundary effects, the numerical model is extended to 60 m wide, 40 m height at left boundary, 30 m height at right boundary, and 15 m thickness. The rock layers are ideal elastoplastic bodies with Mohr–Coulomb failure envelopes. Eight node quadrilateral elements with trilinear displacement are used to mesh the model (see Figure 1). The interface between tunnel structure and surrounding rock is set as the Goodman unit. The physical and mechanical parameters of rock strata are shown in Table 1. In terms of the boundary, the bottom displacements are not allowed in both horizontal and vertical directions; the horizontal displacements on the left and right sides are restrained. The left- and right-side boundaries of the numerical model are assumed to be impervious.

The annular excavation with core rock support method is used to excavate the tunnel, the tunneling process is shown in Figure 2; in which part 1 is the vault step, parts 2 and 3 are arch step, part 4 is the core rock step, and part 5 is the bottom step.

2. 2. RSM Design RSM is an efficient method for experimental design and mathematical modeling [11]. In the current experiment design, six independent variables including horizontal distance (the shortest horizontal distance between the boundary of studied tunnel and the nearby construction), step length (the length between the excavation face of steps 4 and 5 in Figure 2), tunneling depth (the vertical distance between the ground surface and the tunnel vault), width of core rock (part 4 in Figure 2), strength of surrounding rocks, and support strength (the compressive strength of tunnel support structure) are considered and designed by running of the experiments to RSM.

The independent variable parameters and their actual values used for optimization are determined and shown in Table 2, in which the level ‘‘–1’’ and “1” indicates the minimum and the maximum value of each parameter, respectively.

3. RESULTS AND DISCUSSIONS

3. 1. Statistical Analyses The results of 49 runs from simulation are obtained (Table 3) and analyzed by RSM. The model reveals a high value of R2 (0.9714) which shows a strong conformation between the predicted responses values and the simulation results. The model p value is lower than 0.05 which also indicates the high significance of the model, and the p value of all variables are all lower than 0.05 showing the high effect of these variables. In the order from high to low effect on corresponding response, the significant influencing variables are strength of surrounding rocks, support strength, horizontal distance, width of core rock, tunneling depth, and step length.

3. 2. Single Variable's Influence on Vault Settlement The six variables could be divided into controllable and uncontrollable factors. Strength of surrounding rocks, tunneling depth, and horizontal distance are uncontrollable factors since they are unchangeable in the construction process. Width of core

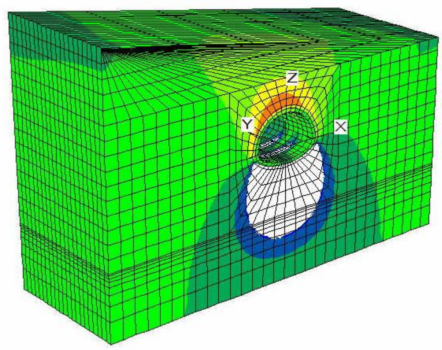

Figure 1. Tunnel model of numerical simulation

TABLE 1. Physical and mechanical parameters of rock strata

Rock layer	Thickness (m)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Internal friction angle (MPa)	Tensile strength (o)
Overlying rock	5	3.81	1.93	0.95	26.5	0.69
Mudstone	14	4.29	2.27	1.14	28.1	1.28
Sandy mudstone	13	4.87	2.58	1.26	29.4	1.13
Sandstone	11	7.42	4.09	1.72	34.0	1.35
Underlying bed	18	7.93	4.38	1.87	35.6	1.42

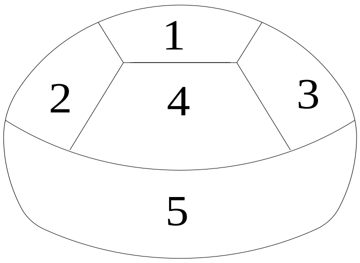

Figure 2. Tunneling process of the annular excavation with core rock support method

rock, step length, and support strength are controllable factors since they can be adjusted for different construction risks. Therefore, in order to better understand the controllable variable's influence on tunnel vault settlement, the fitted curves of the settlement versus each single variable are drawn and shown in Figure 3. It can be known from Figure 3(a) that the tunnel vault settlement is decreasing with support strength exponentially. Similarly, the change law of tunnel vault settlement versus strength of width of core rock and step length could be pointed out from Figures 3(b) and 3(c), respectively.

TABLE 2. Independent variable parameters and their actual values used for optimization

Serial number	Independent variable parameter	Units	Symbol	Level		
				-1	0	1
1	Support strength	MPa	A	20	30	40
2	Strength of surrounding rocks	MPa	B	20	30	40
3	Tunneling depth	m	C	20	25	30
4	Horizontal distance	m	D	10	15	20
5	Width of core rock	m	E	5	7	9
6	Step length	m	F	5	10	15

TABLE 3. The verification index of experimental results of RSM

Source	Sum of squares	Degree of freedom	Mean square	F value	P value	
Model*	229271.93	27	8491.55	27.37	< 0.0001	Significant
A	54216.42	1	54216.42	174.76	< 0.0001	
B	55450.51	1	55450.51	178.74	< 0.0001	
C	12976.40	1	12976.40	41.83	0.0001	
D	40687.08	1	40687.08	131.15	<0.0001	
E	25379.89	1	25379.89	81.81	0.0001	
F	3582.53	1	3582.53	11.55	0.0027	
AB	3608.54	1	3608.54	11.63	0.0026	
AC	210.26	1	210.26	0.68	0.4196	
AD	4155.03	1	4155.03	13.39	0.0015	
AE	1367.58	1	1367.58	4.41	0.0480	
AF	20.25	1	20.25	0.07	0.8008	
BC	1474.81	1	1474.81	4.75	0.0408	
BD	716.87	1	716.87	2.31	0.1434	
BE	10761.08	1	10761.08	34.69	0.0001	
BF	107.39	1	107.39	0.35	0.5626	
CD	809.22	1	809.22	2.61	0.1212	
CE	1322.87	1	1322.87	4.26	0.0515	
CF	468.97	1	468.97	1.51	0.2325	
DE	2260.70	1	2260.70	7.29	0.0134	
DF	148.63	1	148.63	0.48	0.4964	
EF	76.34	1	76.34	0.25	0.6250	
Residual	6514.82	21	310.23	-	-	
Lack of fit	5349.54	20	267.48	0.23	0.9501	Not significant
Pure error	1165.28	1	1165.28	-	-	

* R^2=0.9714

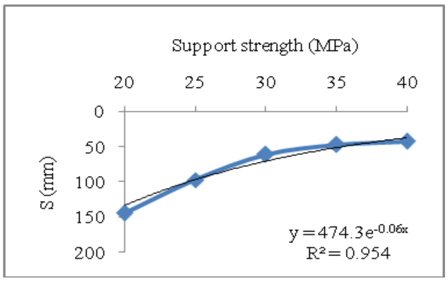

Figure 3 (a). Vault settlement influenced by support strength

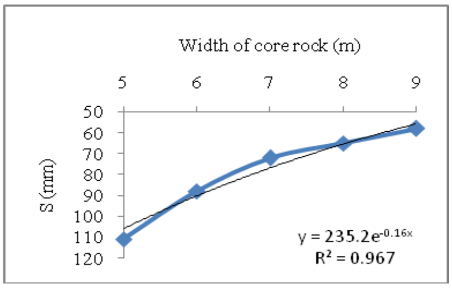

Figure 3 (b). Vault settlement influenced by width of core rock

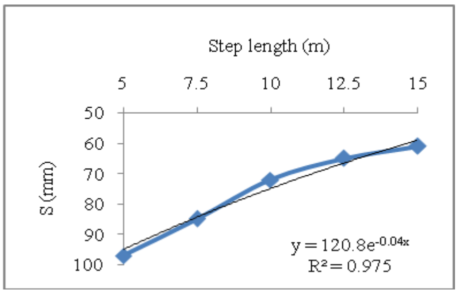

Figure 3 (c). Vault settlement influenced by Step length

3. 3 Interactions of Multi-factor on Vault Settlement Figure 4 shows that when the strength of surrounding rock is c onstant, the vault settlement decreases with the support strength dramatically before the support strength up to 30 MPa. After that, the decreasing rate of vault settlement is declining. The effect degree of support strength on vault settlement is heavily influenced by strength of surrounding rocks, that is, the weaker the surrounding rocks are, the better the controlling effect of support strength is on vault settlement. It is an effective way to enhance the tunnel stability by improving the support strength while the surrounding rocks are weak.

Figure 5 shows that when the tunneling depth is constant, the vault settlement decreases with the increase of support strength dramatically. The effect degree of support strength on vault settlement is heavily influenced by tunneling depth. It is an effective way to control the tunnel vault settlement by improving the support strength. Meanwhile, when the strength of surrounding rock and other factors remain unchanged, the shallower the tunnel is, the more stress released by tunnel excavation will be borne by the support; however, the deeper the tunnel is, the greater the deadweight stress of the overlying rock will be borne by the support.

Figure 6 shows that the effect degree of width of core rock on vault settlement is heavily influenced by tunneling depth. Therefore, setting the width of core rock at a reasonable value could not only be convenient for constructing the support structure, but also reliable for keeping the tunnel vault safe while tunneling.

4. CASE STUDY

The Xiao-guan tunnel in Guiyang underground railway is selected to this case study. The minimum values of tunnel vault settlement according to the previous RSM design are considered at the optimum amount of controllable variables. Using RSM, five desirable solutions of controllable variables are proposed in Table

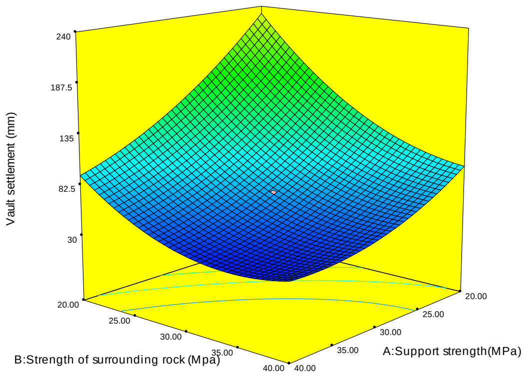

Figure 4. Response surface under the interaction of surroundingrocks strength and support strength

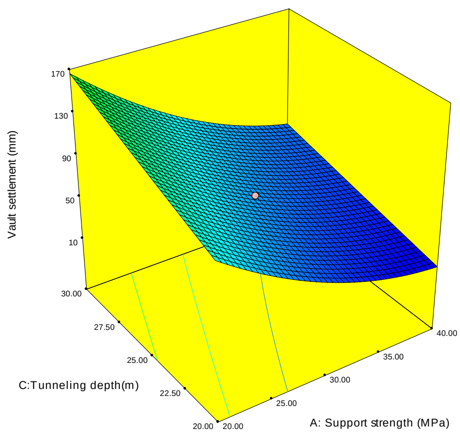

Figure 5. Response surface under the interaction of tunneling depth and support strength

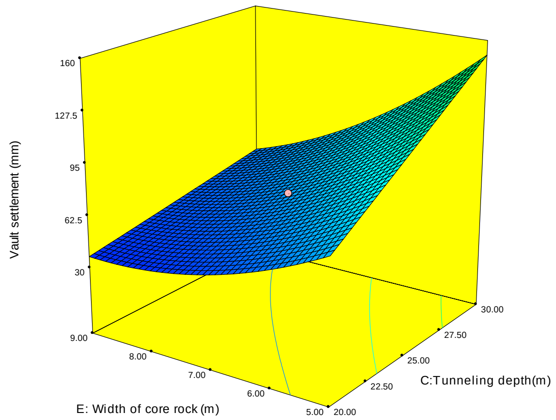

Figure 6. Response surface under the interaction of width of core rock and tunneling depth

5. The desirability of each solution is all larger than 0.915 indicating the optimization is acceptable. One can use each of five solutions including optimized support strength, width of core rock, and step length to achieve desirable responses.

According to solution No. 1, the tunnel support structure is designed as rock bolt of Φ20 mm×L3300 mm, shotcrete of 500 mm thickness, and tunnel lining of 700 mm thickness. Figure 7 shows that the simulated tunnel vault settlement is equal to the solutions in Table 4. Table 5 shows the value of vault settlement from field test, simulation, and RSM are basically the same, the relative error between the three is small, RSM can be reasonably used to study the vault settlement.

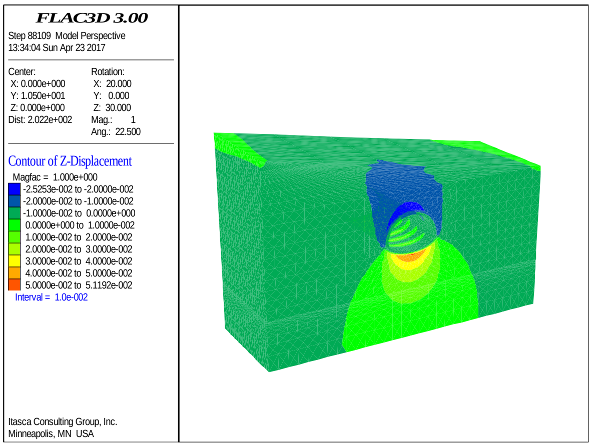

Figure 7. Distribution contours of tunnel vertical displacement

TABLE 4. Optimum additive ratios and corresponding responses

Number	Known conditions						Solutions	Desirability
	Support strength (MPa)	Tunneling dept (m)	Horizontal distance (m)	Strength of surroundding rocks (MPa)	Width of core rock (m)	Step length (m)	Vault settlement (mm)	
1	39.86	28.7	25.3	18.2	7.87	15	24.7964	0.9235
2	39.71	28.7	25.3	18.2	7.87	15	24.8003	0.9235
3	39.65	28.7	25.3	18.2	7.91	15	24.8050	0.9235
4	39.49	28.7	25.3	18.2	7.92	15	24.8161	0.9234
5	38.06	28.7	25.3	18.2	8.96	15	27.4789	0.9152

TABLE 5. Values error analysis for vault settlement

Data source	Value (mm)	Absolute error (mm)	Relative error (%)
Measured in field test	28.000	-	-
Simulation calculated	25.253	2.747	10.41
Solution of RSM	24.796	4.204	15.9

5. CONCLUSION

In the present study, RSM was used to study the influence of uncontrollable factors and controllable factors on the vault settlement characteristics of unsymmetrically loaded tunnel excavated by the annular excavation with core rock support method. Based on the findings and results, the following conclusions can be drawn:

1) In the order from high to low effect, the significant influencing variables are strength of surrounding rocks, support strength, horizontal distance, width of core rock, tunneling depth, and step length.
2) By analyzing the interactions between controll-able and uncontrollable factors on vault settlement, it can be concluded that the influence of uncontroll-able factors on vault settlement can be weakened by optimizing the controllable factors by RSM.

3）The tunnel vault settlement increases with tunneling depth exponentially, and exponentially decreases with support strength, strength of surrounding rocks, horizontal distance, support strength, width of core rock, and step length, respectively.

4) The value of vault settlement from field test measurement, simulation calculation, and RSM solution are basically the same, which implies that RSM is a powerful statistical tool to seek the optimal parameters in tunnel construction.

6. ACKNOWLEDGEMENT

This study was financially supported by the China Scholarship Council (201808420379), Science and Technology Innovation Team Foundation of Hubei Province Education Department (T201823), and Natural Science Foundation of China (51668018).

7. REFERENCES

1. Civalek, B. Ozturk, A. Yavas., "Nonlinear transient dynamic response of clamped rectangular plates on two-parameter foundations by the algorithm of the singular convolution", ***International Journal of Science & Technology***, Vol. 2, No. 2, (2007), 165-177.
2. Seki, S., Kaise, S., Azetaka, S., et al., "Model experiments for examining heaving phenomenon in tunnels", ***Underground Space Technology***, Vol. 23, (2008), 128–138.
3. Liu, X., Chen, H., Liu, K., & He, C. "Model test and stress distribution law of unsymmetrical loading tunnel in bedding rock
4. mass", ***Arabian Journal of Geosciences***, Vol. 10, No. 7, (2017), 184. doi.org/10.1177/1045389X19844009
5. Lin, L. I., Chuan, H. E., & Ping, G. E. N. G. "Study of shaking table model test for seismic response of portal section of shallow unsymmetrical loading tunnel", ***Chinese Journal of Rock Mechanics and Engineering***, Vol. 30, No. 12, (2011), 2540-2548.
6. Lei, M., Peng, L., & Shi, C. "Model test to investigate the failure mechanisms and lining stress characteristics of shallow buried tunnels under unsymmetrical loading", ***Tunnelling and Underground Space Technology***, Vol. 46, (2015), 64-75.
7. Sun, X., Chen, F., Miao, C., Song, P., Li, G., Zhao, C., & Xia, X., "Physical modeling of deformation failure mechanism of surrounding rocks for the deep-buried tunnel in soft rock strata during the excavation". ***Tunnelling and Underground Space Technology***, Vol. 74, (2018), 247-261.
8. Gascoyne, M., Stroes-Gascoyne, S., & Sargent, F. P. , "Geochemical influences on the design, construction and operation of a nuclear waste vault". ***Applied Geochemistry***, Vol. 10, No. 6, (1995), 657-671.
9. Lee, C. J., Wu, B. R., Chen, H. T., & Chiang, K. H. "Tunnel stability and arching effects during tunneling in soft clayey soil". ***Tunnelling and Underground Space Technology***, Vol. 21, No. 2, (2006), 119-132.
10. Wu, W., Zhu, H., Lin, J. S., Zhuang, X., & Ma, G. "Tunnel stability assessment by 3D DDA-key block analysis".***Tunnelling and Underground Space Technology***, Vol. 71, (2018), 210-214.
11. Xue, Y., Zhang, X., Li, S., Qiu, D., Su, M., Li, L., ...& Tao, Y., "Analysis of factors influencing tunnel deformation in loess deposits by data mining: a deformation prediction model". ***Engineering Geology***, Vol. 232, (2018), 94-103.
12. Zhang, D. B., Zhang, Y., Shen, Z., Cheng, T., & Bai, Y. , "Evaluation and optimization of parameters in the measurement for airborne scanner using response surface method". ***Measurement and Control***, (2019). doi.org/10.1177/0020294019837992

Multi-factorial Analysis on Vault Stability of an Unsymmetrically Loaded Tunnel Using Response Surface Method

D. Zhang[a,b], Z. Zhang[a,c], T. Cheng[a], X. Zhao[d]

[a] *School of Civil Engineering and Architecture, Hubei Polytechnic University, Huangshi, China*
[b] *Department of Civil and Environmental Engineering, National University of Singapore, Singapore*
[c] *School of highway engineering, Chang'an University, Xi'an, China*
[d] *School of Civil Engineering and Architecture, East China Jiaotong University, Nanchang, China*

P A P E R I N F O

Paper history:
Received 17 August 2019
Received in revised form 29 August 2019
Accepted 12 September 2019

Keywords:
Response Surface Method
Annular Excavation
Vault Settlement
Unsymmetrically Loaded Tunnel

چکیده

این مطالعه به بررسی خصوصیات اسکلت طاق یک تونل بارگذاری نشده نامتقارن است که با استفاده از روش پشتیبانی سنگهای هسته ای توسط خاکبرداری حلقوی حفر شده است. از روش پاسخ سطح ((RSMبرای طراحی آزمایشات ، ارزیابی نتایج با هدف بهینه سازی پارامترهای طراحی برای کاهش شهرک طاق استفاده شده است. ابتدا پارامترهایی مانند فاصله افقی ، طول پله ، عمق تونل زنی ، عرض سنگ هسته ، استحکام سنگهای اطراف و استحکام تکیه گاه بررسی شد و سپس یک معادله رگرسیون چند جمله ای مرتبه دوم برای پیش بینی پاسخ های حلقه طاق بدست آمد. درصد سهم ، اعتبار مدل و اثر پارامترهای مختلف و همچنین اثر متقابل آنها با استفاده از واریانس ((ANOVAبررسی شد. از نظر بالا از اثر کم ، این پارامترها مقاومت سنگهای اطراف ، استحکام تکیه گاه ، فاصله افقی ، عرض سنگ هسته ، عمق تونل زنی و طول پله است. نتایج نشان داد که تأثیر عوامل غیرقابل کنترل (یعنی مقاومت سنگهای اطراف ، عمق تونل زنی و فاصله افقی) در محل طاق می تواند از طریق تنظیم فاکتورهای قابل کنترل (به عنوان مثال عرض سنگ هسته ، طول پله و مقاومت پشتیبانی) کاهش یابد. . علاوه بر این ، روش پیشنهادی در این مقاله با نتایج حاصل از اندازه گیری تست میدانی و محاسبه شبیه سازی که تأیید امکان سنجی آن را تأیید کرده است.

doi*: 10.5829/ije.2019.32.11b.08*