Experimental Study on the Effect of Implementation and Progressive Failure of Pre-lining Method for Tunnel in Soft and Broken Surrounding Rock

Jinxiu Yuan [1), 2)] ***and Daoyuan Wang*** [1), 2)*]

[1)] Department of Road and Bridge Engineering, Hebei Jiaotong Vocational and Technical College, Shijiazhuang, Hebei, 050091, China.
[2)] School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang, Hebei, 050043, China.
[*]Corresponding Author. E-Mail: wtg-888@163.com.ORCID: 0000-0003-3328-0283

ABSTRACT

By conducting a large-scale three-dimensional model test in an outdoor experimental tank, this paper aims to reveal the effect of the pre-lining method during the full-section excavation and the mechanism of the progressive failure and instability. Firstly, the test purpose, test site, similar materials, test process and measuring systems are described in detail. Then, the effect of the pre-lining method is obtained through the comparative analysis of the internal displacement, surrounding rock pressure and pre-deformation of advanced core soil. Finally, the mechanisms of progressive failure and instability are explored by studying the instability process and the deformation evolution under different loadings. The results show that the convergences of vault and sidewall are decreased by 25% and 80%, the pre-convergence rate is reduced by 20 %~30 % and the longitudinal influence range of advanced core soil is decreased by nearly 60% under normal load conditions. The instability process of the tunnel is peeling-slip-collapse of rock mass and the collapse is finally formed with 2 m depth of sidewall, 1.4 m depth of vault and 1.2 m depth of excavating face. The limit displacement value of railway double-track tunnel under the geological condition of completely weathered V-grade granite is given.

KEYWORDS: Tunnel engineering, Weak and broken surrounding rock, Pre-lining method, Effect of implementation, Progressive failure, Model test.

INTRODUCTION

In the mid-1970s, based on the theoretical analysis and field tests of hundreds of tunnels, the Method of ADECO-RS (Analysis of the Controlled Deformation in Rock and Soil) is created by Professor Piertro Luardi (Peilad et al.,1995; Li et al., 2015). The core idea of this method is to adopt appropriate pre-convergence deformation control method of advanced core soil to create favorable conditions for full-section excavation, so as to achieve the purpose of average pricing of the tunnel and to solve the difficult problems of construction cost, construction schedule and construction safety caused by the change in the state of the surrounding rock mass during the construction process. To date, this method has been widely used in the construction of large-scale tunnels in European countries with high mechanization levels. However, in China, this method has been only used in the Liuyang river, Taoshuping tunnel and Wolong tunnels.

In theory, the characteristics of rock mass are the key factors to decide whether to set pre-lining (Cui et al., 2021; Hassan et al., 2021; Ismail et al., 2020). At present, the commonly used methods for controlling the pre-convergence deformation of advanced core soil are as follows: blocking the excavation face with fiber-reinforced shotcrete, pre-reinforcement with anchor or pipe shed, full-section reinforcement with rotary jet-grouting piles,… etc. Many scholars have conducted a

Received on 10/4/2021.
Accepted for Publication on 4/7/2021.

large number of research studies on the action mechanism, construction parameters and action effect of conventional methods mentioned above (Wang et al., 2017; Wang et al., 2019; Cui et al., 2017; Sun et al., 2014; Liu et al., 2009). However, the research of the pre-lining method is rarely mentioned in the existing studies. In the works of (Gerhard et al., 1986), the pre-lining effect of Bua Metro tunnel in Paris was studied by numerical simulation method and the result showed that the surface subsidence can be reduced by about 70% compared with the NATM. Guan et al. (2003) analyzed the stress and deformation of the tunnel constructed with the pre-lining method in Japan and the design parameters, including pre-lining thickness, range and overlapping length were also determined. By compiling a three-dimensional finite element calculation program, Wang et al. (2005) explored the advantages of the pre-lining method in controlling variation of strata and disturbance range of surrounding rock, the results showed that the pre-lining method can reduce the ground deformation range and the maximum surface subsidence is less than 15 mm, only 30% of the NATM in a shallow urban tunnel. Based on the Hongliangying tunnel, Sun et al. (2017) discussed the safety factor of pre-lining under different arch spacing and different arch foot reinforcement methods by numerical simulation. The results showed that the smaller the distance of the steel arch shelf, the higher the safety factor and the overall safety factor of pre-lining cannot meet safety requirements when the local weakening degree of pre-lining is more than 50%. Taking the Beijing subway as a prototype, the influence analysis of different types of concrete pre-lining has been carried out in the study of Wang et al. (2017). The results showed that displacement is mainly produced in the process of grooving and pouring, while that of side walls and vault is mainly under pressure and tension, so the pre-lining poured by plain concrete is easy to be destroyed and the pre-lining should be enhanced in project design. Han et al. (2017) proposed that the effect of pre-lining can be enhanced by improving the concrete mix proportion and the performance of the shotcrete machine.

The above research results have provided good guidance for the stability control in the soft tunnel when adopting the full-section excavation method. However, the existing studies have mainly focused on the effect of pre-lining on controlling formation displacement in a specific engineering numerical method while ignoring the failure evolution law of excavation face in the process of destructive test under different loading conditions. Also, the convergence of advanced core soil under pre-lining and the control level of extrusion displacement of tunnel face are rarely investigated by the large-scale three-dimensional model test.

Therefore, in this paper, the pre-convergence deformation, convergence deformation, face extrusion displacement, the law of surrounding rock pressure, mechanism of failure and instability and the limit displacement value of stability determination are studied in the process of full-face excavation under conventional load and overload conditions. The research results are expected to provide a reference for full-face mechanical excavation with pre-lining.

Model Test Design

Test Purpose

(1) Through setting working condition A and working condition B, the construction mechanical response during full-section excavation with or without pre-lining set is compared and analyzed and then, the effect of pre-lining method in controlling tunnel stability is searched. (2) Through setting working condition C, the failure mechanism and the limit displacement value of stability are obtained in the process of loading step by step. The test grouping is shown in Table 1.

Table 1. Working conditions of test

Working conditions	Experiment contents
A	Pre-lining, full-section excavation
B	No pre-lining, full-section excavation
C	Progressive loading to instability failure

Test Site

The whole process of test is completed in an outdoor model test tank. The building size of the test tank is 7.11 m*6.7 m*4.5 m, the size in groove is 2.5 m*6.0 m*4.0 m and the entrance and exit of 1 m*1 m are set. The distance between the lower side of the opening and the bottom side of test tank is 0.5 m. The outdoor test tank is shown in Figure 1.

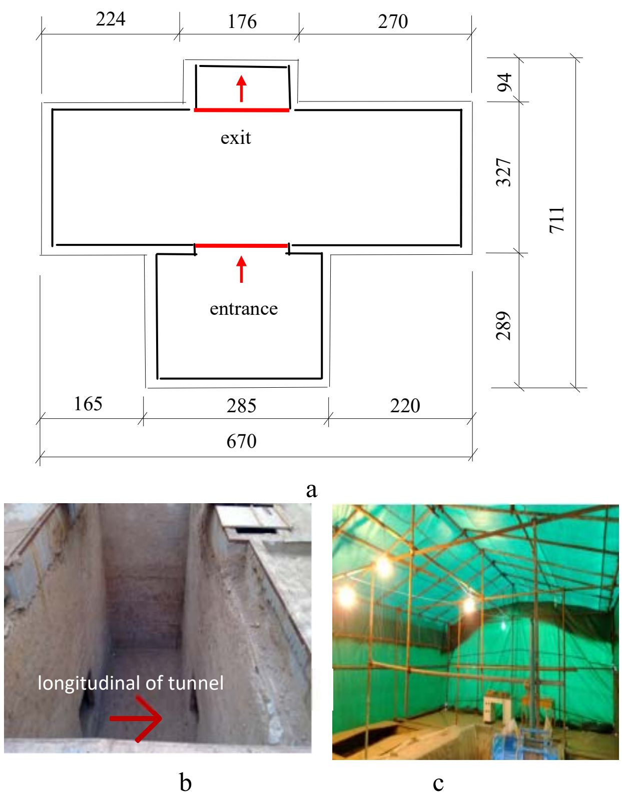


Figure (1): The outdoor test tank (unit:cm). (a) Plane dimensions, (b) Site of test tank, (c) Outdoor canopy

Overview of Prototype

The prototype of this model test is Dongkeling tunnel, which is a two-way railway tunnel with a design speed of 250 km/h and a total length of 4947 m. The tunnel passes through fully weathered granite and sand shale and the V-Grade surrounding rock section accounts for 44% of the total length of tunnel. The section of tunnel is horseshoe-shaped, with a span of 13.72 m and a height of 11.8 m. The primary support thickness of tunnel is 28 cm and the thickness of secondary lining is 55 cm. The burial depth of tunnel is 20 ~ 550 m. The mechanical parameters of strata revealed by fully weathered granite are shown in Table 2.

Table 2. Mechanical parameters of strata

Rock mass	Density [g·cm^{-3}]	Cohesion [kPa]	Friction angle[°]	Modulus of elasticity [MPa]
Fully weathered granite	1.85～2.15	10.9～49.5	25.5～36.1	12.3～25.1

Determination of Similar Materials

According to the existing space in test tank and the actual tunnel height of 11.8m, the geometric similarity ratio is set as 17:1 and then the height of model test tunnel is determined to be 69.5cm (less than the limit of 70cm of allowable test model height in tank). According to the field soil density and model test soil density, the density similarity ratio is set as 1.5:1. Taking density similarity ratio and geometric similarity ratio as basic quantities, the similarity ratios of other parameters are deduced according to π theorem. The elastic modulus similarity ratio is set as 17:1, the cohesive force similarity ratio is set as 17:1 and the internal friction similarity ratio is set as 1:1. Gypsum is selected as the similar material of the pre-lining model, its prototype is C30 concrete (the elastic modulus is 30 GPa) and the elastic modulus of the similar material of the pre-lining is 1.7 GPa according to the similar ratio of elastic modulus. The paste water ratio is set as 1.55:1 by orthogonal test. Representative samples are taken from vault, side walls and bottom of the actual filling tunnel model. Shear strength parameters (cohesion and friction angle) and elastic modulus are obtained by conducting direct shear tests and uniaxial compression tests, respectively.

By mixing sand, soil, talcum powder and water, indoor geotechnical experiment with orthogonal proportion method is carried out. The final reasonable mix proportions and relevant mechanical parameters are obtained, as shown in Table 3.

Table 3. Proportioning of similar materials and test results of mechanical indices

Mass ratios of materials			Results of test		
Talcum powder	Fine sand	Silty clay	Cohesion [kPa]	Friction angle[°]	Modulus of elasticity [MPa]
6	10	50	0.87	29.7	0.91

Test Process and Key Points

The test was carried out in the outdoor test tank and the test tank was divided into three sections (section of pre-lining, section of no pre-lining and reserved section). The test process mainly includes: filling in test tank, construction and excavation of pre-lining and application of destructive test load.

(1) Filling in Test Tank

In order to reduce the boundary effect, a layer of polyethylene plastic film was set around the test tank. The soil was filled layer by layer and the thickness of single layer was controlled within 20 cm. Each layer was compacted and roughened between the upper and lower soil layers, as shown in Figure 2.

a b

Figure (2): Filling and roughening of soil layers. (a)Setting of polyethylene plastic film, (b) Roughening treatment of soil layer

(2) Construction of Pre-lining Structure

In order to ensure the accuracy of excavation contour, a tunnel outline mould with plywood and excavation cutter knife are self-made. The self-made cutter knife is shown in Figure 3. According to the geometric similarity ratio and the actual excavation footage of 1 m, the blade length is set to 5.8 cm (equivalent to one excavation cycle) and 11.6 cm (equivalent to two excavation cycles). First, the position and range of pre-lining were determined by plywood mould before excavation. Second, the pre-lining excavation was carried out with the self-made excavation cutter knife and it should be noted that the excavation face of tunnel lags behind a working cycle of pre-lining. Third, gypsum and water were mixed at a ratio of 1.55:1 to simulate the pre-lining and the mixture was injected into position of pre-lining. Finally, the whole section of soil was excavated (see Figure 4) and the excavation process was simulated.

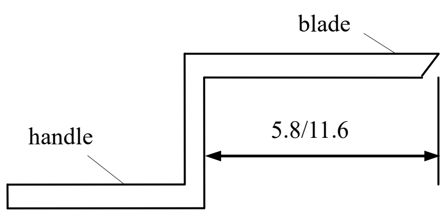


Figure (3): Self-made cutter knife of test (unit: cm)

Figure (4): Excavation of soil

(3) Application of Destructive Test Load

According to the test purpose, this model test includes excavation test and destructive test. During the destructive test, the sand bag loading method was adopted and the weight of each bag of sand was 50 kg. The load was applied in three stages and the single stage load was 1.3 kPa. It should be noted that a thin layer of fine sand and wood board should be laid on the top of model test tank in advance to achieve uniform loading before destructive test load is applied. The field loading is shown in Figure 5.

a b

Figure (5): The site of load application. (a) Boards for uniform loading, (b) Sand bags for heaped load

Measuring Equipment and Layout

In the process of this model test, three monitoring sections of I-I, II-II and III-III were arranged, as shown in Figure 6 and each monitoring section includes two displacement measuring lines (vault and side wall) and three pressure measuring lines (vault, side wall and invert), as shown in Figure (7a, b). Each monitoring section for advance core soil includes one point of earth pressure and three points of extrusion displacement of excavation face (see Figure 7(c)). MOI's FBG displacement meter and micro earth pressure gauge were used for test and the test equipment is shown in Figure 8.

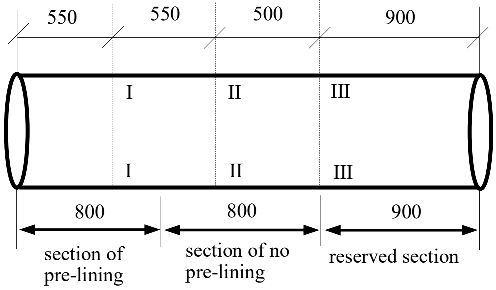


Figure (6): Monitoring of section (unit: mm)

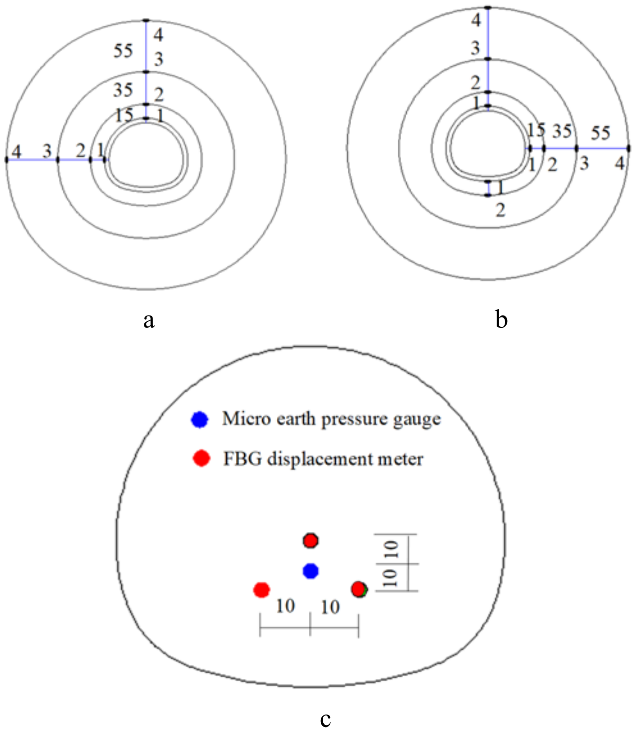


Figure (7): Layout of monitoring line and points (unit:cm). (a) Convergence monitoring points, (b) Pressure monitoring points, (c) Advanced core soil monitoring points

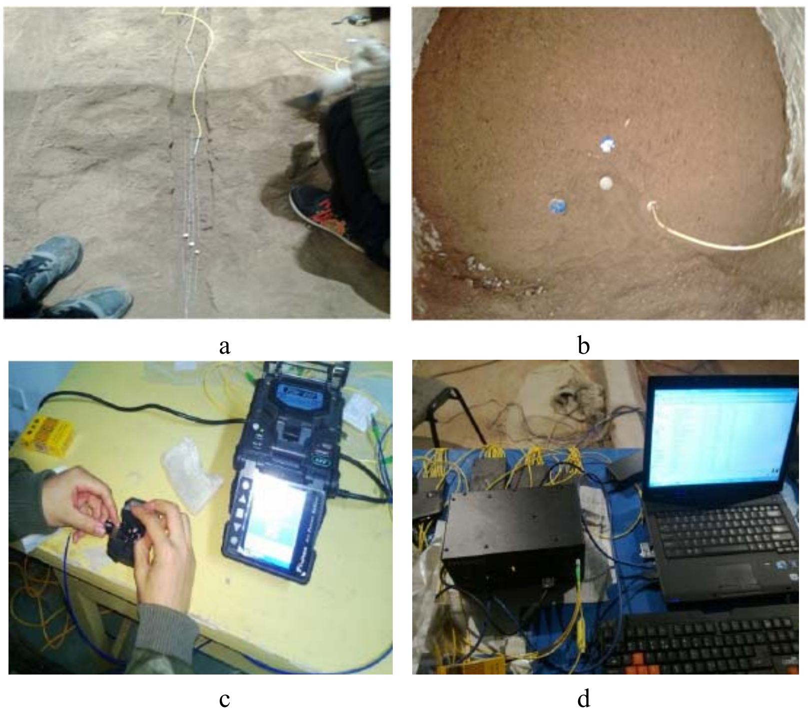


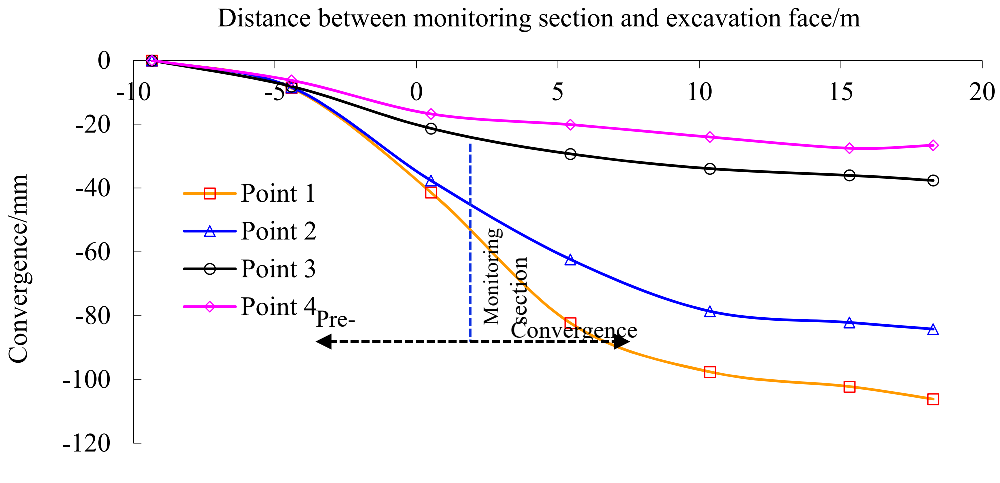
Figure (8): Equipment of monitoring. (a) Layout of grating, (b) Layout of pressure gauge, (c) Melting instrument of optical fiber, (d) Demodulator of optical fiber

Effect Analysis of Pre-lining Method

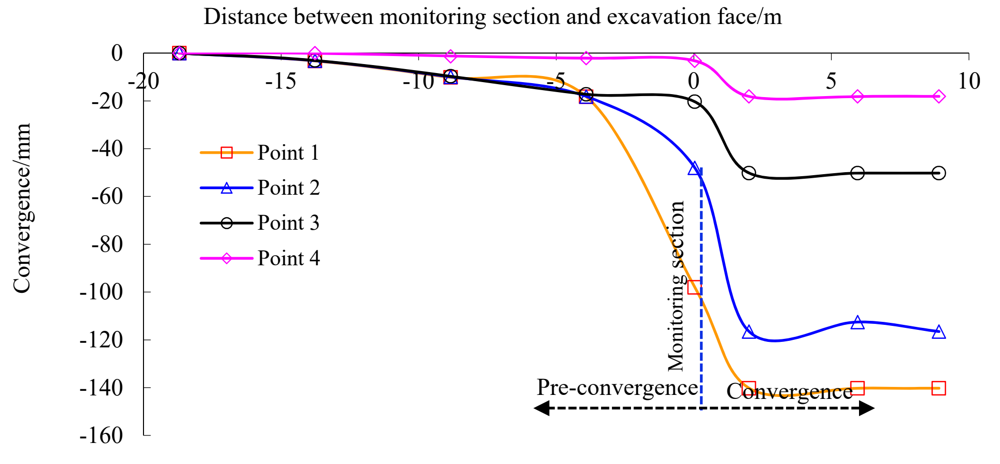
In order to facilitate comparative analysis, the test results are converted into corresponding prototypes for analysis.

Comparison of Convergence Deformation

The convergence deformation studied in this paper consists of two parts: pre-convergence deformation before excavation face reaches monitoring section and convergence deformation after excavation. In order to facilitate comparing and analyzing the effect of convergence deformation under different working conditions (see Table 1), the change rules of convergence of each measuring point on measuring lines of vault and side wall in Figure 7(a) are shown in Figures 9 and 10.

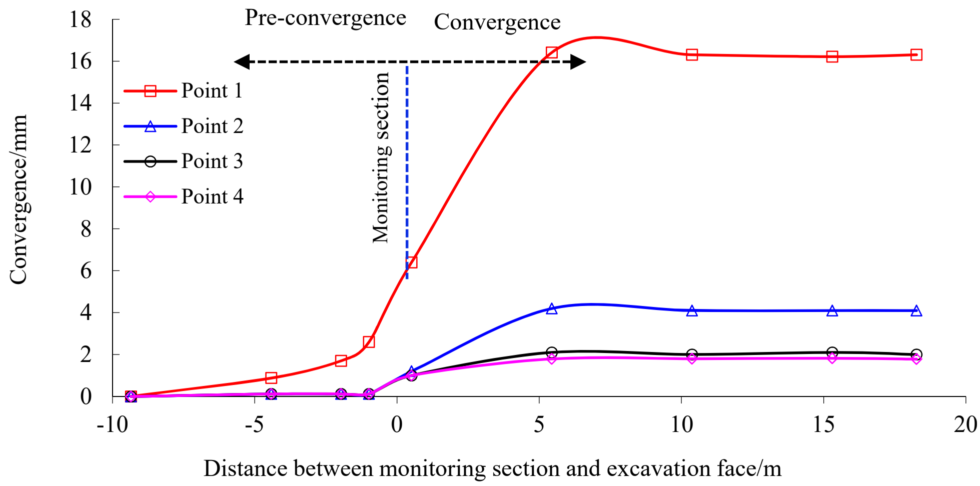


a

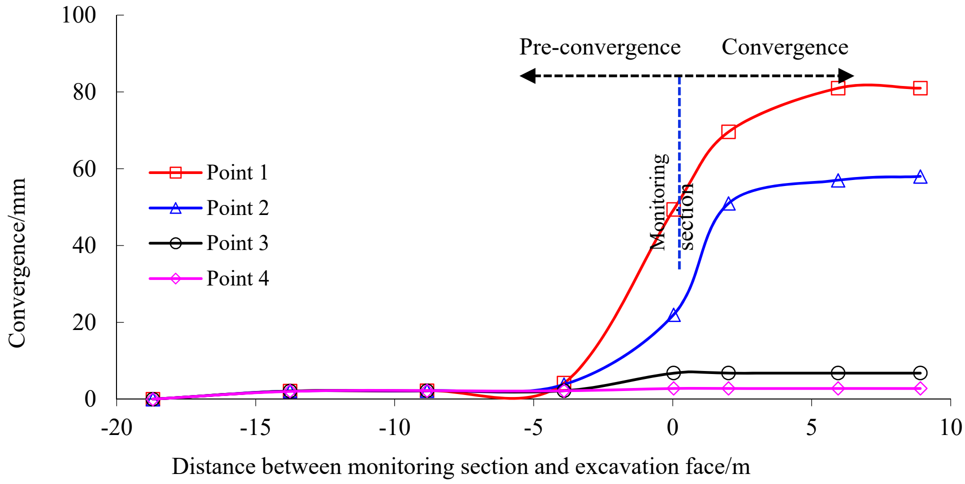


b

Figure (9): Displacement of vault. (a) Working condition A, (b) Working condition B



a



b

Figure (10): Displacement of side wall. (a) Working condition A, (b) Working condition B

It can be seen from Figures 9 and 10 that:

(1) For fully weathered granite stratum, the settlement of vault is larger than the horizontal displacement of the sidewall in process of tunnel excavation. Under working condition A and working condition B, the maximum displacement of vault and sidewall is at the monitoring point 1. The maximum displacement values of vault under working condition A and working condition B are respectively 106mm and 140mm and the maximum displacement values of sidewall under the two working conditions are respectively 16mm and 81mm. The results show that the application of pre-lining structure can effectively limit the development of tunnel deformation. The deformation control level is increased by 25% and 80%, respectively and the control effect of horizontal deformation is more significant than that of vault settlement.

(2) Taking the horizontal convergence survey line of sidewall as an example, the distances of survey points 2, 3 and 4 from tunnel excavation profile are 2.25m, 8.5m and 14.45m, respectively. Under the condition of setting pre-lining structure, the horizontal displacement of measuring points 2, 3 and 4 is small and the displacement values are within 4 mm. Similarly, under the condition of no setting pre-lining structure, the horizontal displacement of measuring points 3 and 4 is also small and the displacement values are with 7mm. The comparison shows that the radial disturbance range of surrounding rock is reduced by 70% in the whole process of excavation due to the construction of pre-lining.

(3) With the excavation face moving forward, the pre-convergence deformation of advanced core soil has occurred before excavation face reaches monitoring section. The pre-convergence deformation of vault and sidewall accounts for 70% and 61% of the total convergence deformation under condition B. However, the pre-convergence deformation of vault and sidewall accounts for 40% and 39% of the total convergence deformation under condition A and the pre-convergence rate (ratio of pre-convergence deformation to total convergence deformation) is reduced by 22% to 30%. The monitoring results strongly illustrate that pre-lining method is very effective in controlling pre-convergence of core soil in front of excavation face.

Extrusion Displacement of Excavation Face

Under working condition A and working condition B, the change rule of extrusion displacement of monitoring sections I-I and II-II with excavation sequence is plotted in Figure 11. Each excavation step represents a model length of 5.8 cm, which corresponds to actual length of 1 m.

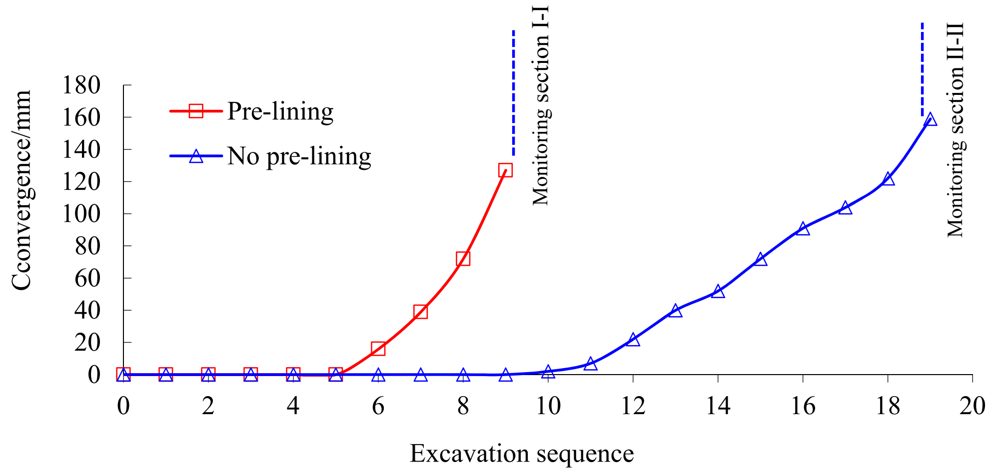


Figure (11): Extrusion displacement of excavation face

It can be seen from Figure 11 that when the excavation face is far away from the monitoring section, the extrusion displacement of excavation face is almost not affected by the unloading of excavated soil under the two conditions. Under working condition A, when the excavation face is about 4 times excavation step (equivalent to 0.3 times of tunnel span) from the monitoring section I-I, the extrusion displacement of excavation face at the position of monitoring section I-I begins to increase before the extrusion displacement reaches the maximum value of 126 mm when the excavation face reaches the monitoring section I-I. Under working condition B, when the excavation face is about 9 times excavation step (equivalent to 0.7 times of tunnel span) from the monitoring section II-II, the extrusion displacement of excavation face at the position of monitoring section II-II begins to increase. The extrusion displacement reaches the maximum value of 159 mm when the excavation face reaches the monitoring section II-II. It can be clearly seen from the above data that the pre-lining structure can effectively reduce the disturbance range of advanced core soil during the whole excavation process; the influence range of setting pre-lining becomes 57% less than that of setting no pre-lining.

Surrounding Rock Pressure

The distribution of surrounding rock pressure around tunnel with three monitoring sections is plotted in Figure 12.

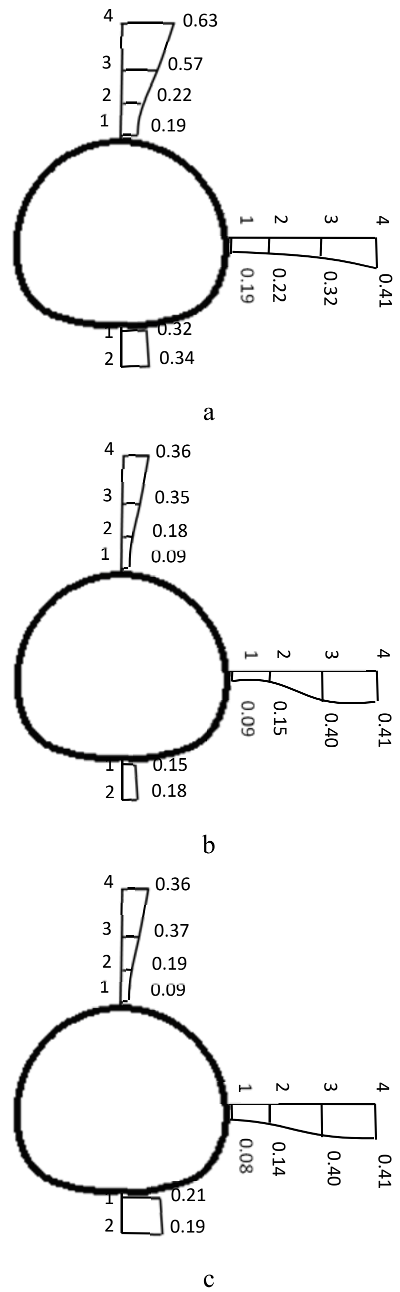


Figure (12): Distribution of surrounding rock pressure in different monitoring sections (unit: MPa). (a) Monitoring section I-I, (b) Monitoring section II-II, (c) Monitoring section III-III

It can be seen from Figure 12 that:

(1) The distribution law of surrounding rock pressure in the three monitoring sections is consistent with the theoretical solution law of tunnel stress in semi-infinite space. The radial pressure around tunnel is relatively small. With the extension to the deep part of surrounding rock, the pressure gradually increases and finally approaches the initial pressure of the stratum.

(2) Taking surrounding rock pressure of vault and sidewall as an example, the surrounding rock pressure on the contour of monitoring sections II-II and III-III under condition B is about 0.09 MPa, while the surrounding rock pressure on the contour of monitoring section I-I under working condition A is about 0.19 MPa and the difference between the two working conditions is 1.1 times. The reason for the difference is that the radial deformation around tunnel is limited by pre-lining structure; the stress of surrounding rock is not fully released, so its load directly acts on the pre-lining structure.

(3) The above mechanical change law and action mechanism prove that pre-lining structure is an effective advanced pre-lining method to deal with weak and broken geological zones with poor self-stabilizing ability.

Analysis on the Process of Instability and Failure

Tunnel structure is a geometrically invariant system with multiple constraints. Local strength failure is not necessarily unstable, but excessive deformation will cause inevitable collapse. Based on the catastrophe theory, the evolution rule of instability failure, the instability criteria of convergence and extrusion displacement are explored during progressive loading.

Description of Tunnel Instability Process under Different Levels of Loading

In the process of loading step-by-step, the stability of inner wall and excavation face of tunnel is monitored continuously. During the first-stage loading process, there is no obvious change in the inner wall and excavation face of tunnel. During the second-stage loading process, the slight peels first occur in the inner wall of sidewall (see Figure 13 (a)) and the transverse cracks appear on the excavation face (see Figure 13(b)). During the third-stage loading process, large-scale peeling, sliding and local collapse of pear shaped occurred at the sidewall and the radial depth of collapse area is about 12 cm, which corresponds to the actual engineering depth of 2 m. Then the vault and excavation face of tunnel collapse and lose stability, respectively, the final collapse depth of vault and excavation face is 8 cm and 7 cm, corresponding to 1.4 m and 1.2 m of the actual project. The actual situation and size of collapse of sidewall, vault and excavation face are shown in Figure (13c, d, e, f).

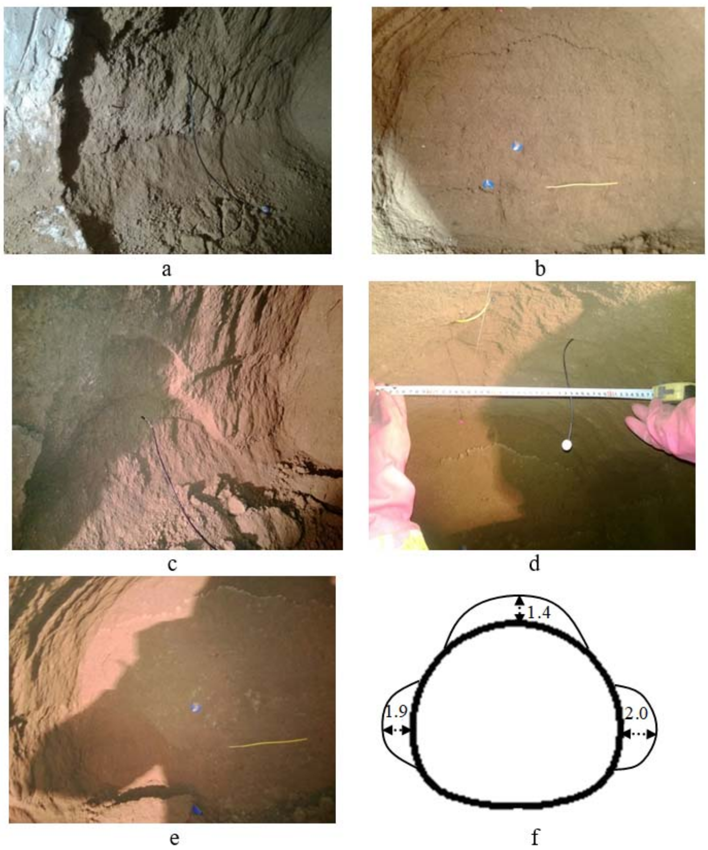
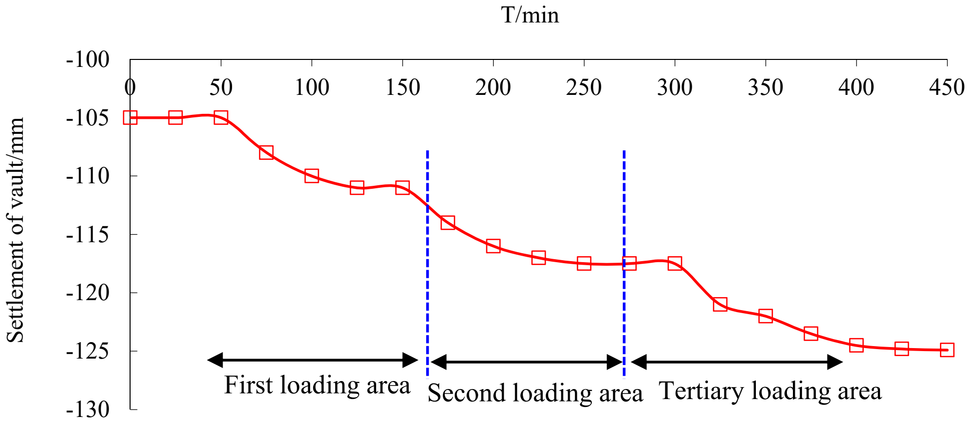


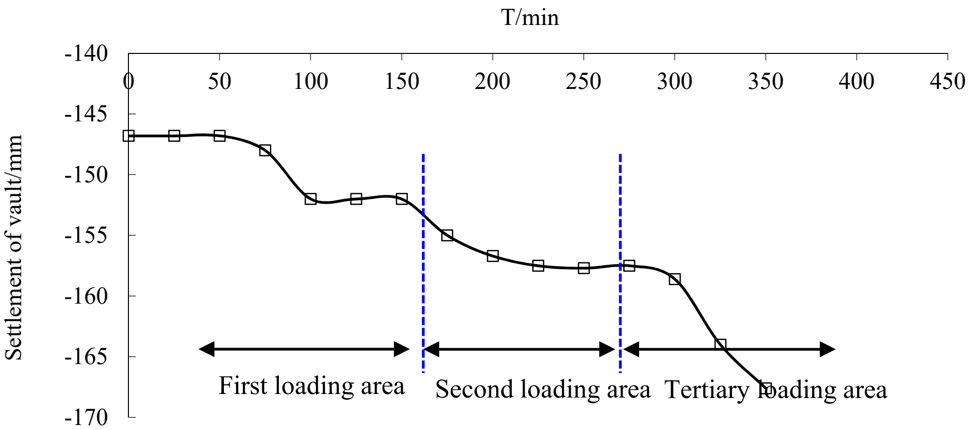
Figure (13): Instability process of tunnel (unit:m). (a) Peeling of sidewall, (b) Transverse crack of excavation face, (c) Collapse of sidewall, (d) Measurement of collapse range of vault, (e) Instability collapse of excavation face, (f) Collapse depth of actual engineering

Deformation Evolution of Tunnel under Different Levels of Loading

The deformations around tunnel and extrusion displacement of excavation face during the progressive loading process are plotted in Figures 14~16.

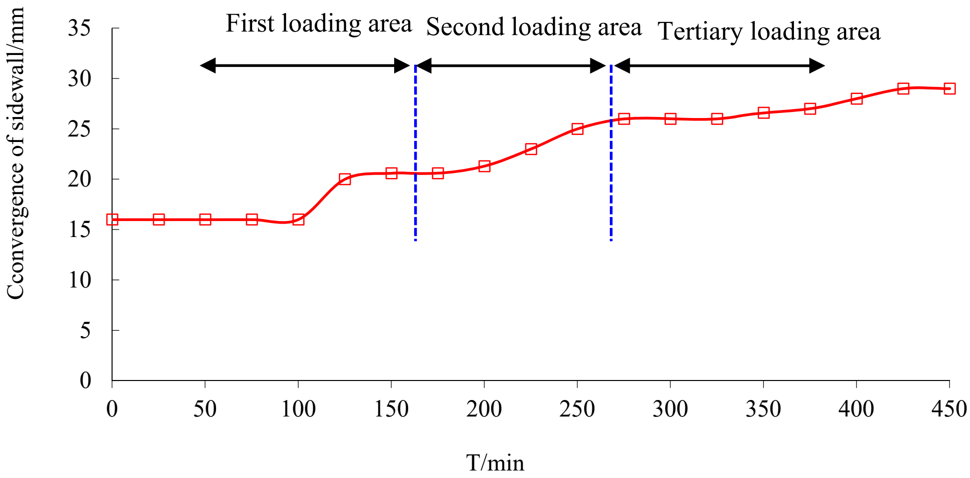


a

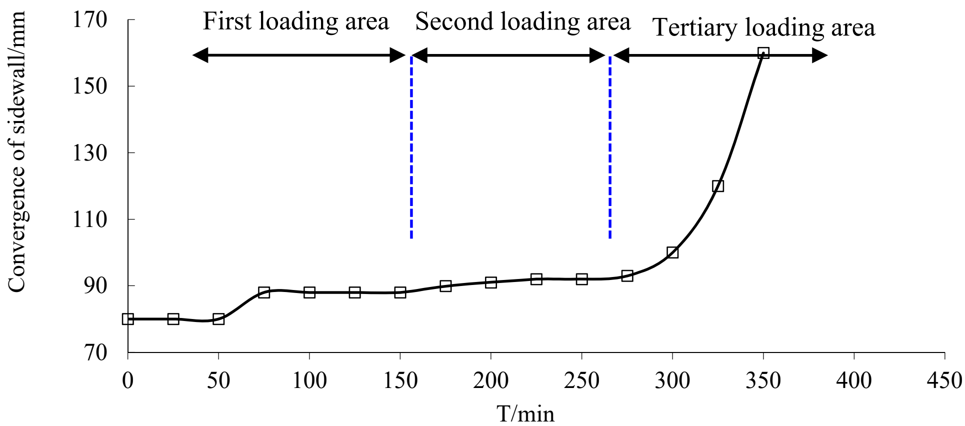


b

Figure (14): Vault settlement under different levels of loading. (a)Working condition A, (b)Working conditions B



a



b

Figure (15): Sidewall convergence under different levels of loading.
(a) Working condition A. (b) Working condition B

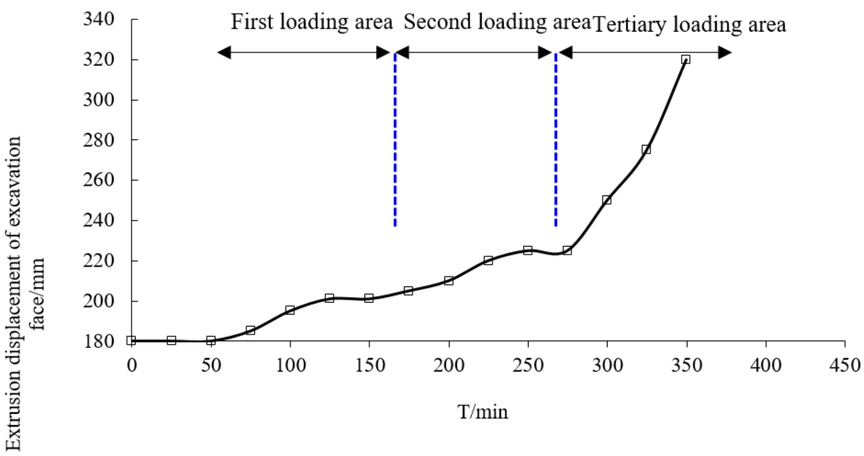


Figure (16): Extrusion displacement of excavation face under different levels of loading

(1) From the settlement of vault and the convergence of sidewall during the loading of all stages in Figures 14-15, it can be seen that the deformation of tunnel with pre-lining method presents evolution rule of “rapid growth in initial stage and stability in later stage” under the given load of all levels, which shows that the tunnel with pre-lining can maintain stability under the given load of all levels. In the first two stages of loading, the deformation of tunnel without pre-lining is similar to that of pre-lining, but on the whole, the deformation value is larger. After the third stage of loading, the deformation of tunnel increases abruptly and presents the situation of non-convergence. According to the catastrophe theory, the vault settlement of 157 mm and horizontal convergence of 93 mm corresponding to the initial stage of third-stage loading can be taken as the limit displacement of stability.

(2) In the process of destructive loading test, the core soil in advance of monitoring sections I-I and II-II has been excavated, so only the extrusion displacement of monitoring section III-III is monitored during the loading at all levels. Before 270 min, the extrusion displacement of excavation face increases first and then tends to be gentle during the first and second loading processes (see Figure 16). When the third-level load is applied, the extrusion displacement of excavation faces increases abruptly and the soil is peeled, slipped and collapsed. So, the extrusion displacement of 225 mm at the initial stage of the third load can be taken as the limit displacement value of stability of excavation face.

CCONCLUSIONS

(1) In completely weathered granite stratum, the pre-convergence deformation of vault and sidewall accounts for about 70% and 61% of the total deformation without pre-lining structure. However, the pre-convergence deformation of vault and sidewall accounts for 40% and 39% of the total deformation with pre-lining structure. Therefore, the method of pre-lining can effectively control the settlement of vault and convergence of sidewall and the control level is increased by 25% and 28%, respectively and the pre-convergence rate of vault and sidewall for advanced coil soil in front excavation face is reduced by 30% and 22%, respectively.

(2) In the double-track railway tunnel project, the longitudinal influence length of excavation process on extrusion displacement of excavation face is about 0.7 D (D is the tunnel span) without pre-lining structure and the longitudinal influence length of excavation process on extrusion displacement of excavation face is about 0.3 D with pre-lining structure. By setting the pre-lining structure, the longitudinal disturbance ranges of the advanced core soil affected by excavation can be reduced by 57%.

(3) The pre-lining method can effectively limit convergence deformation and longitudinal disturbance range of the advanced core soil, but the surrounding rock pressure around tunnel is increased by 111%. From the perspective of stress, this method is suitable for geological sections of shallow buried and weakly broken with poor self-stability.

(4) Under the given load conditions at all levels, the deformation of pre-lining section presents the evolution characteristics of “rapid growth in initial stage and stability in later stage”, but the deformation of no pre-lining section increases abruptly and presents the situation of non-convergence under the third-stage load. The rock mass of sidewall, vault and excavation face of tunnel appears the phenomenon of “stripping-sliding-collapse” instability and the corresponding final collapse depth is 2.0 m, 1.4 m and 1.2m, respectively.

(5) The reference limit displacement values for stability determination of double-track railway tunnel under fully weathered V-grade granite geological conditions are as follows: the vault settlement is 157mm, the horizontal convergence is 93 mm and the extrusion displacement of excavation face is 225mm.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding Statement

The authors appreciate the support from the Natural Science Foundation of Hebei Province (No. E2021419001).

REFERENCES

Cui, G.Y., and Ma, J.F. (2021). "Application of the isolation layer in tunnel crossing the soft and hard rock and subjected to seismic waves". Jordan Journal of Civil Engineering, 15, 241-252.

Cui, G.Y., Wang, D.Y., and Ni, S.Z. (2017). "Model tests on bearing characteristics of basalt fiber-reinforced concrete tunnel linings". Chinese Journal of Geotechnical Engineering, 39, 311-318.

Gerhard, S. (1986). "Das Verfahren des mechanischen Voreinschneidens im Tunnelbau". Strassen und Tiefbau, 26, 32-34.

Guan, B.S. (2003). "Technical character: Idea of tunnel construction and its development". Railway Construction Technology, 3, 1-6.

Han, G.S., Wagn, X.Y., and Wang, B.H. (2017). "On some issues with concrete during tunneling by the mechanical pre-cutting method". Modern Tunneling Technology, 54, 9-16.

Hassan, R.F., Risan, H.K., and Hussein, H.A. (2021). "Seismic behavior of reinforced concrete rectangular water tank on grade with wall opening". Jordan Journal of Civil Engineering, 15, 12-29.

Ismail, S., Kaddah, F., and Raphael, W. (2020). "Seismic soil structure interaction response of midrise concrete structures on silty sandy soil". Jordan Journal of Civil Engineering, 14, 117-135.

Li, B., Hong, Y., and Gao, B. (2015). "Numerical parametric study on stability and deformation of tunnel face reinforced with face bolts". Tunneling and Underground Space Technology, 47, 73-80.

Liu, Z., Liu, J.G., and Zhang, Y. (2009). "New technique of rotary horizontal jet grouting for arched tunnel pre-support". Chinese Journal of Rock Mechanics and Engineering, 28, 59-65.

Peila, D., Oreste, P.P., and Rabajoli, G. (1995). "The pretunnel method: A new Italian technology for full-face tunnel excavation: A numerical approach to design". Tunnelling and Underground Space Technology, 10, 367-374.

Sun, B. (2017). "Research on the parameters of pre-lining support in loess tunnel". Journal of Railway Engineering Society,9, 77-82.

Sun, F.F., Liu, T., and Lei, G. (2014). "Research on the applicability of adeco-rs in a water-rich sand stratum". Modern Tunnelling Technology, 51, 171-178.

Wang, D.Y., Cui, G.Y., and Xu, H.L. (2019). "Research on the technology of resisting dislocation of fiber-reinforced concrete lining on cross-fault tunnel". Journal of Railway Engineering Society, 12, 71-75.

Wang, D.Y., Yuan, J.X., and Li, J. (2017). "Deformation prediction of pipe roof in shallow soft portal section of tunnel considering construction feature and its application". Chinese Journal of Rock Mechanics and Engineering, 36, 716-724.

Wang, X.Y., Wang, T., and Li, K. (2017). "Experiment on ground deformation during tunneling and pre-arch stress by pre-cutting method". China Journal of Highway and Transport, 30, 101–109.

Wang, X.Y., Zhang, Z., and Lu, H.L. (2005). "A study of ground deformation when excavating tunnel in soil by mechanical pre-cutting method". Rock and Soil Mechanics, 26, 140-144.