Final Lining Concrete Quality Control of a Loess Tunnel with an Integrated Approach

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Abstract. Sound quality and conditions are essential for the final lining of a tunnel with composite lining system in soft ground in terms of safety and durability. To build high quality tunnels, defects in lining concrete, such as cracking, should be under control in terms of type and pattern, as well as magnitude. In practice, the reasons for tunnel lining concrete cracking are always unique and various among cases or even different sections of a tunnel. For the quality control of a tunnel, which is preliminarily designed with the analogical method, design and construction revising is often required during the tunnel construction, since the design and construction of a modern tunnel are considered as a dynamic process. Considering how the experiences and information from the earlier built sections can be effectively implemented or checked in the following building rounds of a tunnel project, this contribution presents a case of tunnel construction quality control with an integrated approach, with special reference to the final lining concrete cracking control. In this case, the lining concrete cracks in several sections seem beyond the planned allowable values in the early construction stage, in terms of types and size. With the information on the features of the cracks in the lining, as well as the behaviours of both the lining and tunnel surrounding rocks, the reasons for the cracks are analyzed, and the results are applied in an integrated mode to the cracking control in the subsequent construction.

1. Introduction

In the recent decades, various tunnels and underground structures have been built to meet the requirements for underground spaces, especially in the fields of transportation and urban infrastructures in China. At the same time, there is a general tendency of following a higher standard of quality. Of a tunnel in soft ground, sound quality and conditions of the concrete lining are required in an increasingly rigorous mode to meet the high standard requirements in terms of both safety and durability. To build high quality tunnels, the damage to the lining concrete, such as cracking, should be under control in terms of type and distribution pattern, as well as magnitude. In some cases, any crack is not allowed in both design and construction to meet the specified quality control requirement.

However, there seem various reasons for the defects in lining concrete quality control in practical cases. The causes for the lining concrete cracking are intricate in both design and construction quality control. This situation is mainly related to the characteristics of the tunnel and underground structures in both design and construction. For example, in terms of time, the cracking of the final lining concrete may be during construction, at the early stage of the concrete setting, and then on[1-3]. The reasons of the concrete cracking are of project unique, such as in terms of the major influencing factors[4-6]. The stability and safety of the final lining of a tunnel depend on various factors, generally including the conditions of the tunnel surrounding rocks, the features of the tunnel structures, the construction
method applied, as well as the quality control. In simplicity, cracking can be considered due to the imposed loads exceeding the bearing capacity of a concrete member. For example, crack appears as the tensile stress in a concrete lining is over its tensile strength.

The reasons for tunnel lining concrete cracking are always unique and various among cases or even different sections of a tunnel. At present, it seems not a practical way to find a universal model to control tunnel lining concrete cracking. Considering how the experiences and information from the earlier built sections can be effectively used in the following building rounds in a tunnel project, this contribution presents a case of tunnel construction quality control with an integrated approach, with special reference to the final lining concrete cracking control.

2. The situation of the case at early stage

2.1. The tunnel project in general
The Zhangqiao tunnel is one of the loess tunnels in the Menghua Railway line. The tunnel is 1022.7 m long, with the maximum overburden about 100 m. The tunnel is mined with conventional method, with special reference to the principles of NATM.

2.1.1. Lining system. The composite lining system of the tunnel is composed of 30-cm-thick shotcrete primary lining (including steel sets or girders, steel meshes) and 55cm-thick cast-in-place reinforced concrete final lining. Both of the lining layers are with invert to make them a closed supporting. The shotcrete lining and invert are applied with wet process. The design grades of the shotcrete and cast-in-place concrete are C30 and C45, respectively.

2.1.2. Geotechnical conditions. The ground of the tunnel are Pleistocene sandy loess, with the features of brown or yellowish-brown color, medium to dense, and small calcareous concretions, which is characteristics of the old loess in China. The soils are of sandy clay, silty clay or silt, with water content less than their plastic limits, respectively, and the plasticity index is around 8 to 11. The bearing capacity of the ground can meet the design requirement of 200 kPa except for the portal areas. The loess is sound with top-heading and bench excavation pattern, and the faces are stable, with enough long the stand-up time for the implementation of the following building steps.

2.1.3. Building of the final lining. For a tunnel built with conventional method, the general construction procedure of the composite lining system includes application of primary lining system, water-proof and drainage system, and then the final lining, in a two pass mode. In general, the construction procedure of the final lining of the tunnel can be considered in two stages. The invert and filling concrete are first casted in a length of three times of the formwork jumbo length, which is equal to the panel length of final lining arch structure. The low wall of final lining is generally followed in a few days for each section of the corresponding invert. The reserved steel bars of the low wall are designed for the circumferential reinforcement (main bar) of the final lining. The side wall and arch part of are built with pump concrete in panels, with the length same as that of the formwork jumbo. The time lags of the concrete casting between the low wall and arch lining vary from around ten days to more than a month. Around a day or two days later, low pressure grouting is performed to filling the space between the final lining and the primary lining at the crown of each panel. No reinforcement bar is designed for the joints between the final lining panels in longitudinal direction of the tunnel.

Of the construction process of the composite lining, the final lining is generally 30 m to more than 100 m behind the shotcrete lining, with corresponding time lags of about 10 days to a few months.

2.1.4. First adjustment on the composite lining system. There is a water-proof and drainage system between the double-layer lining structures in design. During the construction, the excavation face is “dry”. The conventional function of the water-proof membrane seems useless in terms of building a dry tunnel. Considering a composite lining system without the interlayers being favorable to the
construction in terms of time schedule, cost and avoiding voids behind the final lining at the crown, an agreement on canceling the water-proof membrane and geotextile sheet in the designed composite lining is reached by the involved groups. The composite lining structures are tuned accordingly.

2.2. Features of the concrete cracks in a few lining panels

Cracks are discerned in a few lining panels after following the adjusted lining structures. The sections of the final lining with cracks are 200 m to 300 m from the portal. The cracks are observed shortly after the removing of the formwork jumbo, i.e., the cracking may occur during the final lining building or the relatively short period from then on. The general features of the cracks are as the followings.

2.2.1. Type and occurrence. Considering the relationship between the extension direction of the cracks and the direction of tunnel axis line, the cracks in the tunnel lining concrete can be classified as: longitudinal crack, circumferential crack, and diagonal crack.

The longitudinal cracks extend nearly in a horizontal mode and parallel to the tunnel axis. The cracks appear mainly in the transitional position between the lining crown arch and sidewall, about 5.5 m above the top of the invert filling concrete. A longitudinal crack may run through the two ends of a concrete panel, though most of the cracks are several meters in length. There also appear two or a few longitudinal cracks along a line in a concrete lining panel, with an intermittent extension pattern (Fig. 1). There is no longitudinal crack extending from one concrete panel into the neighbors.

The circumferential cracks extend nearly parallel to a vertical plane in upper part of the tunnel sidewalls, while as circumferential cracks in the arch part of the tunnel lining. The circumferential cracks generally appear above the longitudinal cracks and extend upward, with a length of 1.5 m to 4.5 m, but a few not. In general, the cracks occur at around the middle of the panel length. There appears one circumferential crack at one sidewall of a concrete panel. Some circumferential cracks extend not vertically in the crown part of the lining but oblique upward.

The vertical cracks are in the lower parts of the sidewalls. There may appear one or two cracks in one sidewall, with a feature of nearly halving or trisecting the length of the concrete panel, respectively. In general, the vertical cracks extend from about one meter above the top of the low wall of the lining system, with length of about 2 m.

Diagonal cracks appear in the crown part of some panels. The continuities of the diagonal cracks are not well. There generally is of feature of branch in appearance in a panel.

2.2.2. General features. The types and their occurrences present the general features of the cracks in the lining concrete as the followings. (1) There is a general feature that the longitudinal cracks, circumferential cracks and diagonal cracks appear in specified positions, respectively. (2) The positions and features of the longitudinal cracks are of much typical features, in comparison to that of the other two types. (3) There are generally two longitudinal cracks in each panel, though the extending length of the cracks varying in a large range. (4) Of the occurrences of the cracks, there appears an intermittent pattern along their extension direction, respectively. For each single crack, it is of snake shape, with its width varying (Fig. 3). For the cracks in a line in group, there also appear branch pattern. These features imply their developments under tensile stresses.

2.2.3. Features in details. With a crack width meter, the concrete cracks from a few lining panels are tested at site. It is much clear that the surfaces (sidewalls) of a crack is much rough and in a wavy pattern (Fig. 3). The features of the crack width tested from two typical panels are shown in Figure 4. In general, the longitudinal cracks are much significant. All of the bored cores indicate that the longitudinal cracks cut through the thickness of the final lining and the width of the tested cracks is almost same along the whole thickness. The surfaces of the sidewalls of the cracks also appear much rough and in a wavy pattern. This also implies a tensile stress induced development.
3. Approach to cope with the situation

3.1. The approach in general

As the cracks in the above-mentioned lining panels are recognized as a type of defect in terms of quality control, the measures of preventing cracking in the following building activities are needed there. In practice, the reasons for tunnel lining concrete cracking are always unique and various among cases or even different sections of a tunnel. For the quality control of a tunnel, which is preliminarily designed with the analogical method, design and construction modification or revising is often required during the tunnel construction, since the design and construction of a modern tunnel are considered a dynamic process. To effectively apply and check the experiences and information from the earlier built sections in the following building rounds of the tunnel project, an integrated approach, with special reference to preventing the final lining concrete cracking, is developed by the involved groups. With the information on the features of the cracks in the lining, as well as the behaviours of both the lining and tunnel surrounding rocks, the reasons for the cracks are analyzed, and the results are applied in an integrated mode to the cracking control in the subsequent construction.

3.1.1. Factors under consideration. The cracks in tunnel lining concrete can be due to (1) external loads or deformation[1,3,6], such as in form of ground pressure, water pressure, and differential settlement in foundation or invert, respectively; (2) thermal stress during construction and the early stage of the concrete setting[4,7-10]; (3) construction defects; (4) combination of the above factors. Of this case, the above-mentioned features of the lining concrete cracks imply that the cracking mechanism of the tunnel lining concrete may be attributed to a high tensile stress imposed on the lining concrete under a specified condition. This situation can be simplified as the results of interaction between the three factors: features of the tunnel lining, external loads and thermal stress in the lining concrete, with the influence of the features of the tunnelling procedures under consideration, as shown in Figure 5, in which only three main related parameters are presented for each factor.
3.1.2. Implementation of the approach. As tunneling in soft ground, the monitored behaviors of the surrounding rocks and supports, as well as their interactions, should be evaluated, to meet the requirements of quality control. On the other hand, information sharing and decision making, in which a few groups, including owner or its representatives, contractor, designer or its representative, consultants, are involved, should be timely and effective[11]. A plan, presenting the approach of coping with the situation, the procedure of sampling the information on the behaviors and interactions, how the information shared and decision made in a specified implementation process, is developed by the owner representatives, together with other involved groups, and then is implemented in steps.

Figure 5. Logical chart showing the situation and key factors of lining concrete cracking.

3.2. Reasons on the cracking
The width of some cracks exceeds the project-specified allowable value. To meet the quality control requirement, the first task is to find the mechanism and conditions of the cracking. The above-mentioned features of the cracks preliminarily indicate the nature of the stresses of cracking is tensile. It is preliminarily considered that the building situation of the final lining would have a strong influence on the cracking of the built panels. The thermal stresses in the final lining concrete during the concrete strength development and cooling stage would play a key role in the cracking procedure.

3.2.1. The deformation features of the shotcrete linings. Based on the results of the monitoring on the crown settlement and the excavations convergence of some mined sections of the tunnel, the general features of the deformation of the shotcrete linings of the tunnel are presented in Figure 6. Figure 6 indicates that the monitored deformations of the shotcrete linings are less than 20 mm and the crown settlement values are less than 12 mm. The tendency of the shotcrete linings deformations implies that the excavations under the primary lining system are of stable features since the increments of deformations of both convergence and crown settlement became much small in after the first week and then on. Of the interaction between the shotcrete lining and the final lining, it is therefore deduced that the ground pressures from the surrounding rocks, as well as the shotcrete lining, are not significant, and ground pressures and deformation will not be a major factor in final lining concrete cracking.

3.2.2. The settlement of the final lining invert. After the casting of each final lining invert section, its settlement is monitored to evaluate the contribution of the differential settlement to the stresses of final lining concrete. The results of the monitored sections show that the magnitude of the differential settlements in a lining panel is within 2 mm. The influence of the invert differential settlement on the final lining concrete cracking is neglectable.
3.2.3. The thermal stresses. It is well recognized that thermal stresses can be much significant in concrete cracking during tunnel lining construction and the following cooling period. To evaluate the magnitude of the thermal stress in final lining concrete of the tunnel, the temperatures of several lining panels are instrumented at site. The results of the temperature features of the concrete lining panels are shown in Figure 7. Figure 7 indicates that there is a much large temperature difference between the maximum temperature of the lining concrete and the environmental temperature in average. The temperature difference is about 30 ºC. Following the method of as presented by Klemczak et al. (2017)[12], the maximum tensile stress in the final lining concrete panel is preliminarily approximated, with the consideration of the influence of the contacting conditions between the shotcrete lining and final lining, with and without the interlayer included, respectively. The results imply that the situations under which there is no interlayer being embedded in the calculation models are unfavorable to the cracking control and the maximum tensile stress shows a cracking potential of the lining during the period of concrete setting, as well as the time soon after the removing the formwork jumbo.

![Convergence monitoring results](image1)

(a) Convergence monitoring results

![Crown settlement monitoring results](image2)

(b) Crown settlement monitoring results

Figure 6. Features of the deformation of the shotcrete lining in some typical section of the tunnel.

![Temperature features of the concrete lining](image3)

(a) Panel 1

(b) Panel 2

Figure 7. Temperature features of the concrete lining.

3.3. Readjusting of the building situation and the results

Based on testing and the monitoring data, including the preliminary results from site investigation, features of cracks, the monitoring results of the deformations of ground, shotcrete lining and the invert of the final lining, as well as the features of the potential thermal stresses in the final lining, it is generally accepted by the involved groups that the building situation of the final lining would have a strong influence on the cracking of the built panels. A relatively smooth surface and soft contacting conditions between the shotcrete lining and final lining are favourable to the concrete quality control, with special reference to decreasing the restraint along the contact surface between the two lining layers. And therefore, the structures of the composite lining system are set back to the original design, with water-proof membrane and geotextile sheet between the dual linings. The building situation of the final is readjusted accordingly in the following rounds. The results of following building present the readjusting is reasonable, since the cracking of the new built lining concrete is under control.
4. Conclusions
Based on this case of the final lining concrete quality control during the construction of a loess tunnel with an integrated approach, with special reference to the final lining concrete crack preventing, the following conclusions can be drawn.

(1) To cope with the situation of tunnel final lining concrete quality control, of which the influencing factors would be various and of intricate features, an integrated approach, with project specified considerations, is necessary and effective, such as in the final lining concrete crack preventing.

(2) Considering the dynamic features of modern tunneling, it is beneficial to learn in a tunneling process under the project-specified plan, which presents the approach of coping with the project situation, including the procedure of sampling the information on the behaviors and interactions of the tunnel supports and surrounding rocks, and information sharing and decision-making.

(3) In this case, the dominate factor of preventing the cracking of the final lining concrete seems a relatively smooth surface and/or soft contacting condition between the dual linings, as well as the thermal stress control in the new lining panels.

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