The Construction Scheme Analysis and its Application of the Southern Portal Section of Urban Mountain Large-span Road Tunnel Under Shallow-buried Bias and High Voltage Tower in Zhuhai

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Abstract. The Heibaimian Jiangjun Mountain road tunnel is located in Nanwan District, Zhuhai City. The topography and geological conditions are complicated with challenges of high-voltage tower protection, shadow-buried bias load, under-passing water-supply tunnel and large-span section tunnel. To tackle these extremely unfavourable site conditions, the original construction scheme includes: i) a gravity retaining wall to overcome shadow-buried bias load, ii) a both side drift method with static blasting, controlled blasting, and conventional blasting and a tunnel body using a composite lining with curved wall and invert to resist section deformation of tunnel and protect existing infrastructures. However, this scheme involving multiple blasting techniques has seriously affected the construction progress of the west-line tunnel, becoming the primary threat to construction progress. To solve this problem, an flexible and pragmatic engineering countermeasure with a controllable cost and without sacrificing safety is proposed, by adjusting location of a south construction adit between the east and west tunnels. Besides, improvements on tunnel face excavation method and relative blasting parameters, as well as the optimization of construction scheme at the southern portal section, are proposed to accelerate the construction progress of the west tunnel. The proposed countermeasure provides important technical support for tunnel construction and is successfully applied to this engineering practice.

Keywords: urban road tunnel; shallow-buried bias; extra-large cross-section and large-span; tower foundation; construction scheme analysis

1. Introduction
Hengqin New District in Zhuhai City maintains a good development momentum in recent years. To improve the service of road traffic network, it needs to accelerate the construction progress of Heibaimian Jiangjun Mountain (HJM) road tunnel of. The tunnel is an extra-long road tunnel with shallow-buried, bias and large-span engineering problems [1-3]. Moreover, there are existing infrastructures including adjacent high-voltage tower and closely water-supply tunnel for Macau, which further makes it a great challenge for tunnelling[3, 4].
Such engineering problems have attracted many research efforts. Peng et al. [5] proposed a numerical analysis model for shallow-buried tunnels, by which they explored influence of cavern stability and stress variation of lining structure caused by buried depth and bias. For an urban shallow-buried bored road tunnel, Wang et al. [6] conducted a comparison analysis between Cross Diaphragm with Step Method (CRDSM) and Cross Diaphragm Method (CRDM). Results showed that CRDM is superior to CRM in respect to construction progress and cost. Hao et al. [7] adopted connection tunnel to add horizontal adit after comparison analysis, which well overcame the schedule delay due to complicated geological conditions and tough treatments of collapse areas. By reasonably optimizing construction method conversion from BSDM (both side drift method) used in Grade V surrounding rock to CRDM used in next Grade IV, and the construction period was shortened by 20-day[8]. Yang et al. [9] utilized the numerical modelling method for comparing and selecting the construction schemes of large-span tunnel under-passing high-voltage tower, functioning as solid evidence for decision support. By investigating HJM East Line tunnel construction practice closely crossing water-supply tunnel for Macao, it was found that how underpass tunnel heading beneath water-supply tunnel was excavated reasonably was the key technical problem to be solved. In Fu et al.’s works [10], the micro-vibration blasting technology was used successfully to excavate heading of train tunnel passing under the Shenzhen metro shield tunnel at a very short distance. Also, it pointed out that Sadov's formula, which usually is used to calculate the blasting vibration velocity, was not suitable to estimate the blasting vibration velocity in proximity of protected targets [10].

Taking the construction of HJM urban mountain road tunnel under complicated conditions as engineering background, this study investigates: 1) how the changing engineering factors influence on the construction scheme, and 2) the reasonable modification and optimization of the construction scheme, in order to secure the construction progress and quality.

2. Project summary

HJM tunnel is located in Nanwan District, Zhuhai City, which is a double-tube tunnel with design speed of 60km/h. East Line tunnel (ZK1+195 to ZK4+840) has three lanes with a total length of 3,645 m; while West Line tunnel (YK1+185 to YK4+920) has a total length of 3735m and four lanes near the south portal [1]. The south portals (ZK4+840, YK4+920) scene, as shown in figure 1.

![Figure 1. South portal sites scene (West Line, left)](image)

The tunnel site belongs to the erosional hill landform, with an elevation from 10.0 m to 380.9 m. The tunnel surrounding rock is mainly composed of strongly, moderately and slightly weathered granite, and granodiorite with Grade II to V, where both north and south portals have poor rock up to Grade IV to V. Hydrogeological conditions are simple. The site design basic seismic acceleration is 0.10g. The New Austrian Tunnelling method was adopted to design the tunnel structure. The 3-lane and 4-lane tunnel sections have the three centred curve wall structure, with construction clearance height 4.5m, and width 13.5m and 20.0m respectively. For the 3-lane section, the excavation width is 15.60m to 16.70m and the excavation height is 9.40m to 10.48m with an invert; for the 4-lane section, the excavation...
width and height is 23.44m and 14.06m respectively. The excavation clear distance between the west and east tunnels is around 25m. The shallow-buried bias tunnel occur mainly in the portal sections, and the south portal section of the West Line has a typical challenging excavation condition with 4-lane span, the shallowest depth of 27.36m, and obvious bias. As shown in figure 1.

A high-voltage tower is located on the south portal of West Line. The clear vertical distance between the foundation of the tower and the tunnel arch is 7.33m. The site conditions of West Line south portal are complicated, as shown in figure 1. Besides, the West and East Lines cross the existing water-supply tunnel at YK4+568.323 and ZK4+579.824 respectively, with clear vertical distances of 5.247m and 4.862m correspondingly.

Both north portals of East and West Lines have a better operation site condition. Compared with the west-line portal operation site conditions, bidirectional construction from north and south portal accelerated the hole-through of East Line, and the early hole-through of East Line is good for the West Line to speed up its tunneling progress.

Apparently, the west-line south portal section construction of 4-lane large-span tunnel, and the northward crossing water-supply tunnel with east-line and west-line tunnels at near south portals, would be challenging for tunneling engineering, might cause some significant uncertainty on construction progress, and becoming the most critical factor constrained on the whole project delivery.

3. The Construction scheme with an adit in south section and its improvement

3.1. construction scheme and tunnel holing-through scheduling
The essentials of the scheme, related to construction progress or schedule, are listed as below.
(1) Tunneling operation site arrangement and construction considerations
East Line tunnel is given priority for construction holing-through, which is expected to be finished before February 28, 2022. After that, East Line can provide West Line with an operation site for its north excavation. The five operation sites of the East and West Lines tunneling construction are described as below.

- For East Line, two operation sites (ELN, ELS) are launched respectively at the north and south portals for the bidirectional excavation on January 1, 2020.
- For West Line, the first and second operation sites (WLN, WLS) are also launched respectively at the north and south portals for the bidirectional excavation, on January 1, 2020 and on May 1, 2020 respectively. The second operation site (WLS) located on the south portal is responsible for tunnelling the west portal tunnel section with the critical large-span, shallow-buried and bias conditions and protection a high voltage tower on tunnel top, facing a great technology challenge.
- Also for West Line, the third operation site (WLSA) aiming at constructing west-line tunnel northward, set up at near YK4+620 by means of an adit and East Line(as shown in figure 2), is launched on October 1, 2020.

The assignment strategy, utilizing WLSA to excavate West Line north, is designed to free WLS, so that WLS can focus on tackling the construction bottlenecks at the south portal tunnel section due to 4-lane span, shallow-buried and bias worst conditions and the existing tower, thus control the construction risks for whole project (West and East tunnels).

(2) Critical excavation lines and tunneling progress
According to the above strategy of ELS tunneling obviously going ahead of WLS construction, the critical tunneling lines can be determined as: (1) East Line ZK4+840 to ZK4+620 → construction adit
to West Line → West Line YK4+620 to YK3+285; ② West Line YK4+920 to YK4+875 → West Line YK4+875 to YK4+620.

In the construction scheme, the monthly tunnelling progress rates in surrounding rock Grade II, III, IV, V (3-lane) and V (4-lane), are determined by 150 m/monthly, 110 m/monthly, 70 m/monthly, 30 m/monthly and 15 m/monthly, respectively.

![Figure 2. Tunnelling advance of operation sites and holing-through scheduling](image)

The holing-through scheduling of the East and West Lines was determined by the scheme, as shown in figure 2, and the places and dates of four operation sites (WLS, ELS, ELN and WLN) departure are shown in figure 2.

For East Line, it has a 26-month construction period for hole-through at ZK3+210, construction starting on January 1, 2020.

For West Line, it shares the same construction period for hole-through at YK3+285, construction starting on January 1, 2020. The WLS operation site starting from the south portal will reach Y4+620 on September 3, 2021.

3.2. Performance evaluation and analysis on construction scheme

According to the scheme, four tunnelling units (WLN, ELN, ELS, WLS) started construction at designated sites on January 1, 2020. However, the outbreak of Covid-19 led to a 2-month delay. By May 31, 2020, progress for four construction sites was lower than that determined by the scheme.

From June 2020, three operations sites of WLN, ELN and ELS in the tunnels gradually increased their tunneling rate to a normal level. On July 15, 2020, the operation site of WLS adopted the both-side drift method (BSDM) to excavate the tunnel face and reach a cumulative advance of 1 to 2 meters, which enabled to replace the static blasting with controlled blasting fragment and made it possible to improve the tunneling progress of the 4-lane tunnel. By November 30, 2020, the project progress of the above four operation sites was summarized as below:

1. For WLS, using BSDM to excavate 4-lane tunnel section, the quickest and slowest headings by blasting reached to YK4+784.6 and YK4+845.5, respectively. According to the site monitoring measurement, the risk level of tower from large-span tunneling was acceptable at that time.
2. For ELS, TBEM (three-bench excavation method) replaced with BCM (bench cut method) for tunneling, and the quickest and slowest headings by blasting reached to ZK4+496.2 and 583, respectively. According to the site monitoring measurement and observations, the heading excavation of East Line crossing the water-supply tunnel was very tough, and tunneling advance was small.

doi:10.1088/1755-1315/861/5/052099
(3) For WLN and ELN, using BCM to excavate hard rock by blasting, tunneling progress in this two site was higher than that determined by the scheme. CDM (center diaphragm method) was used previously in the north portal section of West Line (WLN) for tunneling. Then the operation sites of WLS, ELS, WLN and ELN kept forward. After conducting analysis on site deformation monitoring and cumulative tunneling footage, key results are summarized as below.

First, for 4-lane tunnel construction, key performance indicators (KPIs) of with including crown settlement, and cross section convergence comply with all requirements of codes and standards, which secured the 4-lane tunneling process. Typical monitoring result of tunnel section deformation, as shown in figure 3.

![Figure 3. 4-lane tunnel section deformation at YK4+855](image)

The high-voltage tower locating between YK4+840 and YK4+880 had a huge safety risk due to the west-line 4-lane tunnel excavation. The monitoring of tunnel section at YK4+855, as shown in figure 3, indicates that the maximum crown settlement was about 7.1mm, the maximum cross section convergence was about 6.9mm, and the settlement and convergence deformation increased gradually then reached a plateau during tunneling. The risk level of the tunnel structure is acceptable [3]. Deformation monitoring of the high-voltage tower was conducted by a professional team authorized by the electrical company. It was told that the risk level from tunneling was acceptable in the whole tunnelling process.

Second, the east-line tunnel under passed the water-supply tunnel at ZK579.824. There was a little seepage occurring in surrounding rock, which should be paid attention on because it would have a great impact on schedule if it cause destruction on this import water-supply tunnel. Section deformation monitoring of 3-lane tunnel crossing water-supply tunnel at ZK4+580, as shown in figure 4. The section deformation complied with the requirements during undercrossing process. Apart from the influence caused by the deformation of undercrossing tunnel, the hydro and geology of surrounding rock, the immoderately blasting damage of surrounding rock with extremely small clear distance, may increase seepage. Micro-vibration blasting excavation might be on trial [10].

Third, remaining the tunneling method, from July 15, 2020, Grade II to V surrounding rock had reached and even been ahead of the tunneling rate determined by the scheme (see Table 1), which was probably related to the conservative design indicators of the scheme. From July 15, 2020 to November 30, 2020, the tunneling progress of sites were calculated, listed in Table 1.
Table 1. The progress indicator table for tunnel construction.

| Surrounding rock Grade | Construction method | Tunnelling progress rate from sites (m/monthly) | Tunnelling progress rate by scheme (m/monthly) |
|------------------------|---------------------|-----------------------------------------------|-----------------------------------------------|
| II                     | BCM                 | 145 to 155                                    | 150                                           |
| III                    | BCM                 | 130 to 145                                    | 110                                           |
| IV                     | BCM, TBEM           | 100 to 130                                    | 70                                            |
| V                      | CDM, TBEM           | 40 to 80                                      | 30                                            |
| V(4-lane)              | BSDM                | 25 to 35                                      | 15                                            |

3.3. Recommendation for construction scheme

Based on previous analysis, negative impacts would be brought to construction progress and period if the construction adit was located at YK4+620 (near Vehicle Transverse Channel no.7), which were summarized below:

Firstly, the operation site of WLS only born 8% of the entire excavation for West Line Tunnel. The advantages of mucking and construction ventilation were not fully reached, which also left serious vulnerabilities regarding the risk of project duration and construction cost control of the East and West Lines.

Secondly, an operation site (WLSA) was made by utilizing the construction adit. WLSA, from YK4+620, constructed the West Line north crossing water-supply tunnel. It unavoidably faced the complicated technical challenge as the East Line meeting: the clear distance between the West Line at YK4+568.323 and its upper water-supply tunnel was only 5.247m, the blasting excavation was not applicable in the range of 20m from the water-supply tunnel, and the static blasting excavation was recommended.

According to relevant technical regulation, blasting vibration velocity at water-conveying tunnel, generated from underpass construction of West Line, was not greater than 1 cm/s. Sadov’s formula of calculating blasting vibration velocity goes as follows [4]:

\[ Q_m = \left[ R(\frac{V}{K})^\alpha \right]^{\frac{1}{10}} \]

(1)

Where \( Q_m \) represents maximum amount of charge per delay (kg), \( R \) is the distance between blasting center and concerned building (m), \( V \) is allowable limit of blasting vibration velocity induced by blasting. \( K \) and \( \alpha \) represent the coefficient and attenuation coefficient while evaluating the topographic and geological conditions between blasting point and object of protection. For now, \( K=180 \) and \( \alpha = 1.6 \).

According to (1), as \( V=1 \) cm/s , when \( R \) equals to 4.5m, 5.5m, and 20m, \( Q_m \) is calculated as 0.0054kg, 0.0098kg, and 0.4726kg, respectively. Therefore, with CDM or other method to excavate tunnel section of YK4+590 to YK4+550 in West Line, static blasting was almost selected only, and micro-vibration blasting might be on trial also [10].

To utilize the construction adit at YK4+620 to move the operation site of West Line (WLSA) north, it needed to overcome the excavation challenge of tunnel section that under-pass the existing water-supply tunnel from YK4+590 to YK4+550. This tough tunneling caused a significant uncertainty on construction progress. After that, WLSA excavated to YK4+550 north, then gradually recovered a normal tunneling speed.
Apparently, it is worth negotiating for construction adit settled at YK4+620 mentioned in the construction scheme.
As said previously, by the end of November 2020, the actual progress for WLS, ELS, WLN and ELN had been ahead of the tunneling progress rate determined in the scheme, listed in Table 1.

It is worth noticing that construction of 4-lane tunnel under complicated conditions in West Line, had almost overcome the technical challenging. That is to say, at the end of November 2020, large-span tunnel of WLS, a major risk concerned by scheme, whose risk level had been reduced significantly.

Thus, making the best use of the above factors can speed up the construction progress. Just moderately adjusting location of adit, WLS will solved technical challenges and low productivity caused by the under-crossing water-supply tunnel.

After integrating the past one-year tunneling status, accumulated construction experience and deep understanding, the key improvements on the construction scheme are listed below.

(1) Location of construction adit was changed from YK4+620 to YK4+120, as shown in figure 2.
(2) The construction adit was excavated into the West Line at YK4+120 from East Line and formulated an operation site (WLSA) in West Line. The excavation northward should start on April 15, 2021. WLSA avoided the risk from crossing the water-supply tunnel at YK4+568.323, and secured the West Line tunneling north smoothly and accelerated the construction progress of West Line.
(3) The operation site (WLS) of the West-Line south undertook the tunneling tasks of 4-lane tunnel from YK4+920 to YK4+785 and 3-lane tunnel from YK4+785 to YK4+120. WLS increased its tunnelling amount from 8% to 23% of West Line whole length. Furthermore, it also undertook the excavation of tunnel section that under-passed the water-supply tunnel at YK4+568.323, and could utilize unhurriedly the static blasting and controlled blasting method to reduce construction risk.
(4) The area of ELN and ELS was under construction heading towards each other. After revision, East Line Tunnel will connect north-south on November 30, 2021. Compared with the scheme, tunnel holing-through mileage moved 50m closer with south portal, leading to 3-month deduction of connection date, which means construction period of East Line Tunnel has shrunken from 26 months to 23 months.

The north portal of West Line was excavated south, while the operation sites (WLS, WLSA) of the south portal and formulating by construction adit excavated north. After adjustment, West Line will achieve hole-through on November 30, 2021. WLS (operation site) will reach YK4+120 on September 15, 2021. Compared with the scheme, tunnel holing-through mileage moved 90m closer with north portal, leading to 3-month deduction of connection date, which means construction period of West Line Tunnel has shrunken from 26 months to 23 months.
The revised scheme for HJM road tunnel was applied during construction. Improvements were revealed and described here. Timely revision of construction scheme had sped up the progress of West Line Tunnel. Operation site (WLS) had abundant time which enabled a combination of static blasting, micro-vibration blasting, controlled blasting, and blasting to be used for excavation[4, 10].

During the construction, the excessive blasting excavation due to hard surrounding rock might be the reason causing suspending operation and structural damage. In order to avoid those construction risks, below terms should be emphasized again. First, blasting with φ40mm blast hole is a must; Second, both tunneling advance per round and length of blasting hole cannot exceed the designated standard; Third, site management is of vital importance while drilling surrounding rock of Grade II-III. The maximum amount of charge per delay of heading cannot surpass the safety limit of charge [10].
4. Conclusion and Recommendation

(1) The monthly progress of four-lane tunnel construction in West Line is obviously ahead of schedule mentioned in the construction scheme, and heading excavation difficulty of East Line closely under-passing water-supply tunnel exceeds the scheme. Thus, an improvement of shifting the construction adit near the southern portal 500m northwards along tunnel mileage was put forward. Serious potential risk in respect of construction time limit, engineering quality and cost control, due to conservative design of adit, was overcome.

(2) By optimizing the location of construction adit, WLS increased its tunneling amount of West Line from 8% to 23%, taking over the risk of drilling west-line tunnel north passing under water-supply tunnel at a very short distance. WLSA for northern excavation in West Line speed up construction progress of the tunnel by means of adit and East Line. By doing so, both construction period and risk factors could be secured because of the technical advantage in mucking and ventilation of west-line southern portal as well as reasonable distribution of tunneling length and construction risk between two northern excavation operation sites (WLS, WLSA).

(3) For WLS, there was sufficient time to integrate different types of excavation methods including static blasting, micro-vibration blasting, controlled blasting and blasting, so as to meet the strict requirements on West Line’s tunneling section that closely under-passed the water-supply tunnel.

(4) Revised technology regarding construction scheme mentioned in this study has been widely adopted and verified in real cases. Aiming at extremely closed distance excavation of unpass water-supply tunnel, it is recommended to discover the appropriate excavation technology by means of trial with micro-vibration blasting and seismic reduction by empty borehole.

5. References

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