Design and Rapid Construction Technique for Bibanpo High-speed Railway Bifurcation Tunnel

Xinghong Jiang¹,², Ke Li¹, ²*
¹China Merchants Chongqing Communications Research & Design Institute Co., Ltd., Chongqing 400067, China.
²National Engineering Laboratory for Highway Tunnel Construction Technology, Chongqing 400067, China.

Abstract: In China, the construction of high-speed railway infrastructure plays a more and more important role in promoting economic growth. However, because of its large turning radius and incapability in bypassing and avoiding, the length of development line cannot meet the needs of separating tunnel, which has driven high-speed railway tunnel bifurcation structure become a necessity in regions with steep high mountains, gorges, ridges and valleys. In the big excavation area of bifurcation transition section, long construction period and collapse of the surrounding rock often happen. To solve those problems, we proposed a new method with rapid holing through procedure and pre-stressed anchor cable support. The methods go as follows. We put forward an optimized process of excavating and breaking through one side of the tunnel first and drilling back through the other side in consideration of the large excavation area and long construction period. We presented reinforced support system of pre-stressed anchor cable in view of problems including surrounding rocks with no secondary lining, unstable structure and unbalanced load releasing. The system has been applied to Bibanpo tunnel, a project in Shanghai-Kunming high-speed railway. By using this method, all difficulties during construction have been broken through, The study could be used as a valuable example for bifurcation structure construction in urban arterial roads and high-speed railway tunnel with the similar geological conditions such as Chengdu-Kunming high-speed railway, Chongqing-Kunming high-speed railway, and Chongqing-Changsha high-speed railway which are going to be constructed.

1. Introduction
Tunnel bifurcation structure can not only meet the function requirement but also shorten length of development line, smoothen track, reduce slope cutting when train is entering into tunnel, avoid the bridge being divided into two pieces, and save construction cost. It is widely used in highway construction with the similar conditions [1-2]. It is extensively used in diverge and confluence areas in urban tunnel ramps. Take the tunnel project in Chongqing Zengjiayan Bridge as an example. In the project, several three lanes in one tunnel were converted to two lanes in two tunnels with the bifurcation tunnel excavation area of 264.6m², 320.3m², 323.8m² and 297.5m². Apart from bridge, tunnel bifurcation structure is also used in freeway tunnel. China first applied it to Hubei section in Shanghai-Chongqing freeway. In the project, the four-lane large-span tunnel was converted to two lanes in two tunnels with the largest excavation area of over 264m². Compared to highway tunnel, high-speed railway tunnel has smaller bifurcation angle and longer transition distance and super large cross section in transition section is inevitable.
Researchers have carried out systematic studies on large-span tunnel construction where excavation methods including Three Stairs and Seven Steps [3-5], Central Divided Method [3] and Both Side Drift Method [5] are widely used. In those methods, support structures such as long anchor, advanced small duct, advanced large pipe shed and glass fiber anchor are mainly adopted. All the support methods are based on the principle of less disturbance, early support, quick closure and diligent measurement of New Austrian Tunnelling Method. Nevertheless, researches on excavating and getting through one side of bifurcation tunnel first and coping with long-time-no-secondary-lining condition are rare.

In general, problems in the construction of high-speed railway tunnel bifurcation structure are as follows.

1. The excavation area of bifurcation transition section is large. The largest area reaches 340m². Besides, the large-span section directly connects the small interval section, which brings difficulties to deformation control.
2. High-speed railway tunnel has small bifurcation angle and long distance of super-long-span tunnel bifurcation. The conventional support pattern would cause long construction period.
3. Passive support is the conventional support structure for tunnel, yet it cannot effectively support surrounding rocks during the excavation of super-large section tunnel, especially when the rock has no secondary lining for a long time.

To reduce risk and shorten construction time, we cited Bibanpo tunnel construction as an example and proposed an optimized process of excavating and breaking through one side of the tunnel first and drilling back through the other side. Besides, we put forward a new method of rapid construction and pre-stressed anchor cable support. The successful construction proved that those new methods could speed up construction, prevent surrounding rock collapse, and reduce secondary lining eccentric pressure.

2. Engineering Background

Bibanpo tunnel is located in the transition zone of Yunnan-Kweichow Plateau, with a total length of 14756m. It starts from Shangzhichang Village, Hongguo Town, Pan County, Kweichow Province, and goes across the northern section of the Laoheishan Mountain Range to Sanqiutian Village, Housuo Town, Fuyuan County, Yunnan Province. The tunnel has a maximum buried depth of 750m and is the longest tunnel and control project for the Shanghai-Kunming passenger line.

The entrance of Bibanpo tunnel is located in gully of Xiaojiashan Mountain’s foot, and it is connected with the Hejiadi Extra Large Bridge. The length of the bridge-tunnel transition section is less than 6m. The terrain of the tunnel near the entrance is steep with the slope angle of 35°, and the surface covering soil is silty clay and strongly weathered clay rock. The thickness of the covering soil increases as train enters into the tunnel, which has been shown in Fig. 1.

![Fig.1 Location of Bibanpo tunnel and Geological section of bifurcation structure](image-url)
3. The Design Scheme of Constructing One Tunnel at the Entrance and Two Tunnels at the Exit

Code for Design of Railway Tunnels recommends constructing two single-line tunnels if a super-long tunnel or tunnel passes through a soft formation or a bad geological section. Bibanpo tunnel repeatedly passes through faults, rock formation contact zones, high-pressure water-rich areas, coal mined-out areas and other unfavorable geological sections. As a result, it is a Class I high-risk tunnel. To ensure construction safety, the main body of the tunnel adopts double-tunnel and double-line design. However, the entrance of the tunnel adopts single-tunnel and double-line design because its length of development line is short, mountain landslide will happen when high slope is excavated.

Bibanpo tunnel adopts the design scheme of constructing one tunnel at the entrance and two tunnels at the exit, which enjoys the advantages of quickness, cost-effectiveness and safety. The transition section starts from the spot that 923-meter away from the entrance and end at the spot 1363-meter away from the entrance, with a total length of 440m. It has four types of transition sections: D, C, B, and A. The layout plan is shown in Fig. 1, and the section sizes are shown in Tab. 1.

The cross section of bifurcation transition section is various and the process transformation is complicated. As the tunnel span and excavation area greatly increase, the high-span ratio reduces, and the construction difficulty and control requirements steeply increase. The excavation of leading hole shows that the surrounding rock of the bifurcation section is slightly weathered grade III limestone with integrity, strong self-stability and no water leakage. Combining with our previous experience on tunnel construction, we shall respectively adopt bench method, three stairs and seven steps, and Central Divided Method in D-type, C-type and B-type sections to ensure construction safety.

| Section Type | Length L (m) | Breadth B (m) | Height H (m) | High-span ratio (H/L) | Area S (m²) |
|--------------|--------------|---------------|--------------|-----------------------|-------------|
| IIIa         | 35           | 14.10         | 11.96        | 0.85                  | 154.33      |
| D            | 160          | 16.58         | 12.69        | 0.77                  | 172.16      |
| C            | 130          | 19.10         | 13.52        | 0.71                  | 210.26      |
| B            | 110          | 22.11         | 14.57        | 0.66                  | 264.28      |
| A            | 40           | 25.79         | 16.28        | 0.63                  | 338.61      |
| IVb          | 35           | 11.16         | 11.18        | 1.00                  | 102.02      |

The excavation area of A-type section is too large to use the integral deformable formwork jumbo adopted by the D-type, C-type and B-type lining sections. If we choose the conventional excavation process, we shall spend one to two months in renovating the formwork jumbo and the overall progress of the tunnel will be seriously delayed. The excavation area of A-type section is nearly 340m², which is much larger than the conventional two-line high-speed railway tunnel. In the highway project, such as Hanjialing Tunnel on Shenyang-Dalian Expressway, Yabao Tunnel on Nan Ping Expressway in Shenzhen, and Longtoushan Tunnel on Guangzhou City Beltway, the span of excavation section of four-lane single-hole tunnel is less than 22m. Therefore, the construction experience of road and railway tunnel cannot guide the construction of A-type section. The A-type large-span section is directly connected with the small interval section, where the thickness of the rock pillar is less than 2.5m. If the A-type section is first excavated, excavation disturbance will easily cause multiple structural damages of the rock pillar, reduce the bearing capacity, and cause hidden dangers for construction safety.

4. Construction Technology of High-speed Railway Tunnel Bifurcation

The construction process of the A-type large-span section and small interval transition section can be summarized as follows:

(1) the left side of the A-type section → the right side of the A-type section → the left tunnel → the right tunnel.
(2) the left side of the A-type section → the left tunnel → the right side of the A-type section → the right tunnel.

(3) the left side of the A-type section → the left tunnel → the right reverse tunnel → the right side of the A-type section.

The process is shown in Fig. 2. To sum up, if the first procedure is adopted, construction time would be long; deformation control would be difficult; and the rock pillar would be seriously damaged. However, it is a conventional construction procedure with relatively mature experience. The second procedure is conducive to shortening construction period, yet it cannot protect the rock pillar. The third procedure not only shortens the construction period, but also reduces the unfavorable disturbance to the rock pillar when the right side of the A-type section is excavated. During the excavation of the right side, the construction of the left and right tunnel has been finished. As a result, the rock pillar, the support of left tunnel and right tunnel could bear together, which protects the rock pillar. Nevertheless, the left side of the A-type section would have no secondary lining for a long time and its may be stability.

As for bifurcation tunnel, most of the existing researches focus on the load mode and construction method analysis, yet those on optimized construction process of bifurcation transition section are rare [1,6-8], and those on optimal process of different sections are few. The mechanical parameters of surrounding rock in the bifurcation section are shown in Tab.2. By the simulation made by Flac3d, we got the horizontal displacements of the rock pillar in the three construction processes. The results are shown in Fig. 3 and the strain distribution is shown in Fig. 4. After the completion of tunnel excavation in different processes, the horizontal displacement and strain distribution of rock pillar are different. The displacement in the first procedure is larger than that in the second procedure which is larger than that in the third procedure. In consideration of construction time and rock pillar protection, we would choose the third procedure, during which rock pillar keeps good integrity and instability and collapse do not appear.

| Material types       | Elastic modulus E (GPa) | Poisson's ratio ν | Internal friction angle φ (°) | Cohesion c (kPa) |
|----------------------|------------------------|------------------|-------------------------------|-----------------|
| Surrounding rock     | 10.0                   | 0.27             | 39.0                          | 1100            |
| Primary support      | 30                     | 0.2              | /                             | /               |
| Secondary lining     | 33.5                   | 0.2              | /                             | /               |

Tab.2 Computing-mechanical parameters.

![Fig.2 Construction procedure of bifurcation transition section.](image-url)
5. The Support Technology of Bifurcation High-speed Railway Tunnel

The third excavation procedure requires that the left pilot tunnel of A-type section shall be excavated first, and the surrounding rock on the right of the A-type section shall be excavated after the construction of the left and right tunnel. When we adopted central divide method to excavate pilot tunnels, we moved the mid partition left to make it tangent to the contour of left tunnel excavation in consideration of vehicle access, space for ventilation duct and stability of surrounding rock in the left pilot tunnel. The modified Central Divided Method is shown in Fig. 5.

As the left pilot tunnel is excavated first without secondary lining for a long time, the surrounding rock and primary support bear the loose load together. After long-time stress release, the plastic zone would expand deeply, making deformation control more difficult. When the right pilot tunnel is excavated for a long time, the gap of load release rate of surrounding rock between left and right arch is large. Secondary lining eccentric pressure would appear and the safety of secondary lining would be threatened.

Pre-stressed anchor cable, consist of outer anchor head, cable anchor and anchoring section, is a new active support. Pre-stress is produced by anchor cable tension and anchoring is realized. The efficient, flexible and applicable pre-stressed anchor cable has been widely used in strengthening engineering of high embankment and high slope in mountain areas in southwestern and southern part of China. Especially after 2008 Sichuan Earthquake, it is focused, developed and applied to prevent slope instability, and reduce secondary injury, death and economic lose[9-15]. Practice shows that pre-stressed anchor cable enjoys advantages of deep anchoring, technical maturity and high quality. It can effectively restrict surrounding rock damage from deepening and support the left tunnel.

However, the design theory and standard of pre-stressed anchor cable are rare because it is rarely used in tunnel excavation. In most cases, the conventional bolt-shotcrete support and secondary lining can meet the needs of support because the range of surrounding rock looseness is smaller than that of slope instability. When the anchor cable is designed, under the condition of Class III surrounding rock (s=3), the height of loose circle of the tunnel can be calculated in accordance with Code for Design of Railway Tunnels (formula 1). Arch loose load in a longitudinal length unit is $F = \gamma h B = 3404 kN/m$.

We arranged three sets of pre-stressed anchor cables with pre-stress of 300 $kN$ on both sides of the hance to share about 53% of surrounding rock loose load.

$$h = 0.45 \times 2^{-1/2} \omega$$

(1)
Where $\omega$—width influence coefficient, $\omega = 1 + i(B - 5)$, $i$—surrounding rock pressure increase and decrease rate, $i=0.1$.

During the practical operation, we chose anchor cable of 15 meters in consideration of anchorage length and drilling efficiency. We arranged three sets of pre-stressed anchor cables with pre-stress of 300 $kN$ on both sides. The circumferential and longitudinal space is 1.2m and 0.8m.

Fig.5 Construction method of A-type section.

After the numerical simulation calculation of Flac3D, we find that with the support of pre-stressed anchor cable, the maximum depth of plastic zone on hance decreases to 4-5m from 6-8m, and the ranges of plastic zone on arch and hance shrink obviously, which is shown on Fig. 6. As we can see in Fig.7, surrounding rock displacement reduces and the displacement gap between left and right vault shrinks with the effect of pre-stressed anchor cable. In conclusion, pre-stressed anchor cable can control plastic zone range, reduce surrounding rock displacement and decrease structural eccentric pressure.

Fig.6 The distribution of plastic region.
6. Conclusion
The paper takes Bibanpo tunnel in Shanghai-Kunming high-speed railway as an example, explains the design origin, project procedure, support structure, monitoring and measuring methods and result analysis of the bifurcation section. Combining the successful construction experience of bifurcation section of Bibanpo tunnel, we draw into the following conclusions.

(1) Tunnel bifurcation construction method enjoys the advantages of quickness, cost-effectiveness and safety. It has a broad prospect in constructing long and large tunnel where bridge and tunnel are directly connected. However, it should not be applied to poor geological regions because of various types of bifurcation transition section, frequent change of construction method, high risk of construction and control difficulty.

(2) The large turning radius of high-speed railway tunnel and long bifurcation would restrict and delay tunnel construction. The construction method of excavating and getting through one side of the tunnel first, and drilling back through the other side can not only control construction time but also optimize the mechanical property of small spacing section.

(3) The construction method would make the large-span section have no secondary lignin for a long time, which increases the difficulty in controlling surrounding rock deformation. In this condition, pre-stressed anchor cable can be used to support rock, control plastic loose range, reduce stress release, decrease secondary lining eccentric pressure and optimize structure stress.

Acknowledgements
This work is financially supported by National Key Research and Development Program of China (2017YFC08060010, 2017YFC08060003), National Natural Science Foundation of China (41601574), Special Project of Scientific and Technological Innovation for Social Undertakings and People’s Livelihood Guarantee of Chongqing, China (cstc2017shmsA30010).

Reference
[1] Ding, W.Q., Zheng, K.C., Jin, W., 2016. Spatial load-structure calculation method for a deep forked tunnel. China journal of highway and transport. 29: 90-97.
[2] Wei, L.Y., Li, S.C., Guo, X.H. et al., 2011. Study of stability of transition segment for bifurcation tunnel. China Journal of Highway and Transport. 24: 89-95.
[3] Fang, Q., Liu, X., Zhang, D.L. et al., 2017. Shallow tunnel construction with irregular surface topography using cross diaphragm method. Tunn. Undergr. Sp. Tech. 68: 11-21.
[4] Li, P.F., Zhao, Y., Zhou, X.J., 2016. Displacement characteristics of high-speed railway tunnel construction in loess ground by using multi-step excavation method. Tunn. Undergr. Sp.
[5] Zhu, B., Kou, W.F., Xi, J.M. et al., 2016. Numerical simulation research of construction method for shallow buried large section tunnel. Open Civil Eng. J. 10: 578-597.

[6] Li S.C., Wang H.P., Zheng X.F. 2008 Forked tunnel stability analysis and its construction optimization research. Chinese Journal of Rock Mechanics and Engineering 27(03): 447-457.

[7] Wang Z.C., Li S.C., Chen W.Z.. 2007 Deformation monitoring of bifurcation tunnel and countermeasures of construction technologies. Rock and Soil Mechanics 28(04): 785-789.

[8] Wang H.P., Li S.C., Zheng X.F. 2009 Damage analysis and optimum research on construction process for forked tunnel under bias pressure. Rock and Soil Mechanics 30(06): 1705-1710.

[9] Chen, C.S., Xia, Y.Y., 2017. Seismic reliability analysis of slope reinforced with prestressed anchor cable based on global limit response surface. Rock and Soil Mechanics. 38: 255-262.

[10] Yan, M.J., Xia, Y.Y., Liu, T.T., 2018. Limit analysis of reinforced bedding rock slopes with pre-stressed anchor cables under seismic loads. Rock and Soil Mechanics. 39: 1-8.

[11] Ye, H.L., Zheng, Y.R., Li, A.H. et al., 2012. Shaking table test studies of prestressed anchor cable of slope under earthquake. Chinese Journal of Rock Mechanics and Engineering. 31: 2847-2854.

[12] Liu, Y.Q., Liu, X.R., Yang, Z.P. et al., 2016. Field test on anchorage performance of different types of prestressed cables. Chinese Journal of Rock Mechanics and Engineering. 35: 275-283.

[13] Sun, S.W., Wang, W., Zhu, B.Z. 2015. Bearing characteristics of prestressed sheet pile wall in embankment stablization. Rock and Soil Mechanics. 35: 1818-1825.

[14] Wang, Q.B., Zhang, C., Wang, H., Weng X.K., Shi Z.H., Lv R.S., Wang T.T. 2014. Study of coupling effect between anchorage force loss of prestressed anchor cable and rock and soil creep. Rock and Soil Mechanics. 35: 2150-2156.

[15] Zheng, W.B., Zhuang, X.Y., Cai Y.C., Xue F.Z. 2012. Modeling of prestressed anchors in rock slope under earthquake and optimization of anchor arrangement. Chinese Journal of Geotechnical Engineering. 34: 1668-1676.