Study on Structural Cut and Convert Method of Mechanical Undercutting in Large Underground Space

Yi GAO, Shao-hui YU, Yang LI, Peng CHENG, Yu-tian LUO and Chao-yuan FENG

Underground Space Research and Design Institute, China Railway Engineering Equipment Group Co., Ltd., Zhengzhou, Henan, 450016, China

Keyword: Mechanical undercut, Structural cut and convert, Construction method, Underground space.

Abstract. The demand for exploitation and utilization of underground space is more and more intense with the rapid development of cities in China. Domestic and foreign scholars have achieved fruitful results on the related construction technologies. However, the existing technology still has disadvantages. It is difficult to make construction safe and cost-effective in many situations. Based on the study of conventional construction methods and their advantages, combined with the development of underground engineering mechanization and prefabrication, this paper presents a structural cut-and-convert method of mechanized undercutting, which is called CC method and can be applied in large underground space construction, and has also been successfully put into practice. This paper focuses on the structural cut-and-convert method, steel and reinforced concrete composite structure, joint processing and other innovative contents. And corresponding improvements for the method are also made in this paper. Based on the characteristics of this new methods, the feasibility of applying the method to underground spaces with multi-layer, curve-shape, long-distance and prefabricated structures is discussed, and a new solution to the development of urban underground space is also provided in this paper.

Introduction

With the process of China’s urbanization, the demand for the exploitation and utilization of city underground space increases substantially. In the built-up urban area, special boundary conditions such as small space, heavy traffic flow and complex surrounding environment often limit the exploitation of underground space. And the conventional cut-and-cover construction method has gradually failed to meet the needs of maintaining normal function of the city. The demand for a new construction method is getting more and more urgent.

In recent years, scholars at home and abroad have done enormous amount of research on the conventional construction method, and fruitful results have been achieved. Among these achievements, the laying-fabricated-strap method, which is the National Grade Normalized Construction Method, is widely used in urban metro stations. Wang Wenzheng and Xu Jiamin and other scholars [1][2] first applied this method in Beijing Fengtai North Road Station. And the key construction techniques and quality control measures of this method are studied. Shallow-buried tunneling method has experienced considerable development in the country, and the technology has been highly developed. With the efforts of Wang Mengshu, Li Chunfang and other domestic scholars [3][4][5], shallow-buried tunneling method are developed to accommodate shallower burial and various difficult geological conditions. Zhang Guoliang, Ge Ke-Shui and other scholars [6][7] applied PBA method in large-span underground space excavation and emphasized the engineering features of this method such as the superiority in ground settlement control and so on. All these conventional methods have advantages in settlement control and construction cost, but also have disadvantages of long construction period and high construction risk. Especially, all these methods have difficulties in forming underground spaces with large span.

In the aspect of unconventional construction methods, Japanese scholars [8][9][10] such as Sato Takuya and Shimizu Hitoshi developed the HEP & JES method, which has been used in the construction of underpasses beneath existing traffics. Domestic scholars [11][12][13] such as Li
Zhaoping and Chen Jiu-heng absorbed the prefabricated technology of underground engineering abroad, and solved the technical problems such as assembling and lifting, positioning correction, crack control, earthquake resistance and component connection. The construction technology of prefabricated metro station was put forward and successfully applied to Changchun Metro line 2 subway station project. Since 2016, a large-scale and ultra-deep underground garage has been built for the first time in Shanghai [14], prefabricated construction technology has been firstly used in utility tunnel [15] in Beijing Tongzhou Wenlyu District and evaluated as new construction method.

It is noteworthy that, PENG Li-min and other scholars [16] in the study of rectangular pipe jacking technology demonstrated the application of this technology in the development of underground space, and the prospect of this method is also discussed. Modern pipe jacking technology has been widely used in urban underpass, underground interchange and other projects, but not yet applied to urban large-scale underground space development.

Exploration of Construction Method to Form Large underground Spaces

The conventional construction methods and unconventional methods can all form large underground space. And the conventional construction method has the unique advantage of flexibility. The unconventional construction method has the characteristics of mechanization and prefabrication. For the development of urban underground space, how to integrate the advantages of these two types of methods has become a major exploration direction.

Large underground space can be constructed one-time by cut-and-cover method. And can also be formed by a combination of small separate underground spaces. For the current urban environmental conditions, engineering and technological level, building a large underground space at one time is difficult. However, it is feasible to construct a large-scale underground space by constructing a series of small underground spaces and combining these small spaces to form a large underground space.

Figure 1. Traditional CRD method diagram.

Conventional Construction Method (CRD Method)

CRD method is a typical conventional tunneling. Excavation section shown in Figure 1, in order to reduce the disturbance to the surrounding soil, the excavation section is divided into several small parts, each part excavated separately, and then dismantle the temporary cross diaphragm support, the final complete ring secondary support to form a complete tunnel section.

At present, studies are done to improve the conventional CRD method by scholars both at home and abroad. Zhang Jianbin and Cui Xiaopeng, etc. [17][18] the Seven-bench Three-step excavation method and the CRD method, and proposed a method combining the advantages of the two methods.

However, for the construction of large-scale underground space in cities, the CRD method is not the best choice because of its high risk, complicated process and poor working environment. However, the conventional CRD method has many redeeming features, as shown in Figure 1:

① Conversion of structural system;
② Division of the whole cross section and excavation.

Unconventional Construction Method (Harmonica Method)

Harmonica method is developed by Japanese scholars and successfully applied to the construction of the extension of West Osaka, Japan and many other cities underground interchange project. It is the most typical unconventional construction method. As shown in Figure 2, harmonica method
including the following: divide the whole rectangular cross section into several equal rectangular parts; construct each part one by one with rectangular boring machine and prefabricated steel segments as temporary supporting framework; construct the permanent structure using cast-in-situ reinforced concrete, dismantle the redundant interior temporary steel structure, and combine the small parts into whole space.

Harmonica method can be used to develop large underground spaces in the city. But too many temporary support steel segments are used that weakened the advantages of this method. Harmonica method directly applied to the development of large-scale underground space is not yet mature, but there are also many ideas worth learning:

1. Construct with rectangular boring machine;
2. Small spaces between adjacent parts.

**Tentative Plan of Structural Cut and Convert Method**

The conventional CRD method and the unconventional Harmonica method have their own unique advantages in the field of underground engineering. In particular, both the two methods include division and combination of the structure. So, is there a new method which combines the advantages of the two methods for the urban underground space construction?

Efforts were made to integrate the advantages of both two methods including mechanization, adjacent construction, part-by-part excavation and structural system conversion, avoiding disadvantages including high construction risk and poor work condition of CRD method; material waste of the Harmonica method. And a conception, as shown in Figure 3, was formed in this paper based on the study of all underground construction methods, which cuts the cross section into small parts, excavate each part separately with rectangular TBM, and covert the parts into the whole structure. This conceptual method is called Cut and Convert method, hereafter this text will be abbreviated as CC method, which is shown in Figure 3.

**The First Application of CC Method**

The latest research and development of CC method integrated advantages of various methods and tried to avoid the disadvantages. And a pilot project was taken in place on the purpose to test and verify the practice ability and advantage of CC method.

**Project Background**

Based on the pilot project of CREG Underground Parking, the research team successfully applied the CC method at the first time. The underground parking is a single-layer structure with six spans and is 34.5m in width and 85.8m in length. The parking with a building area of 3288m² is designed to contain about 93 parking lots, as is shown in Figure4.
The site of this project is a flat square, with an office building of 6-layer frame structure on the north, an office building of 2-layer masonry-concrete structure on the south, a factory building on the west, and a municipal road on the east. There are a few pipelines buried within the site, only a small amount of water supply pipes, drainage pipes, firefighting pipes and power lines, etc., which are all shallow buried and do not affect the pipe-jacking construction of the project.

The depth of underground water level is about 18m below ground surface. Site stratum mainly constitute the artificial fill, silt and silty clay. The main engineering geological parameters are shown in table 1.

Table 1. Main geotechnical parameters.

| Layer No. | Soil Type       | Natural Density(kN/m³) | Thickness (m) | Lateral Pressure Coefficient (K₀) | Horizontal Foundation Coefficient (MPa/m) | Vertical Foundation Coefficient (MPa/m) | Ground Bearing Capacity f₀(kPa) |
|-----------|-----------------|------------------------|---------------|----------------------------------|------------------------------------------|----------------------------------------|-------------------------------|
| 1         | Artificial Fill | 0.35                   | /             | /                                | /                                        | /                                      | /                             |
| 2-1       | Silty Sand      | 1.66                   | 0.38          | 15                               | 12                                       | 170                                    | 120                           |
| 2-2       | Silt            | 16.8                   | 2.65          | 0.43                             | 12                                       | 15                                     | 140                           |
| 3         | Silty Clay      | 19.7                   | 1.31          | 0.43                             | 22                                       | 22                                     | 140                           |

As shown in Figure 5, a rectangular pipejacking TBM is used for the pipe-jacking construction of this pilot project. With a burial depth of 3m and jacking length of 62.7m, a launching shaft in the east and an arrival shaft in the west are built to achieve the pipejacking construction. The launching shaft is 12m in length and the arrival shaft is 11.15m in length, both the two shafts have an excavation depth of 9.5m. The whole underground parking is formed by 7 pipejacking tunnels, of which the 5 tunnels in the middle are constructed by the TBM with an excavation section of 5×5.7m. After the construction of the 5 tunnels, the TBM is uncoupled into two small independent TBMs to complete the construction of the two side tunnels. The excavation section of the uncoupled small TBM is 5×5.7m, which is half the size of the coupled TBM.

On the whole, the boundary conditions of this project are relatively simple, single-layer structure with 6 spans, straight pipejacking, and soft soil without groundwater.
Formation of Large Underground Space

On the basis of “division-combination” of the original construction method, efforts are made to “combinate” the pipejacking tunnels into one huge underground space. The implemented process of the parking project is illustrated in Figure 6 and Figure 7.

![Figure 6. The formation of underground space.](image)

Following the steps shown in Figure 6, the whole underground parking structure is eventually formed, and the cross section of which is shown in Figure 8.

![Figure 7. Underground parking the final section.](image)

Note from the illustration of Figure 6 and Figure 7, the construction process of large underground space using the CC method is much different from the existing method ever used. At present, the parking project is almost finished, and the CC method has been proved to be practicable. The cross section of the project is shown in Figure 8.

![Figure 8. The actual formation of cross-section.](image)

Innovation of “CC Method”

During the research and engineering practice of CC method, innovative results are achieved, which are shown as follows. In the research process of the new method and engineering practice, summed up a few innovative content.

1) Division and combination of the structure

The division and combination of the structure section is closely related to the architectural composition and structure framework. Taking the underground parking project as an example, the composition of the underground parking is partly depending on the architectural function. The columns of a regular underground parking is arranged as shown in the cross section illustrated in Figure 4(b). The CC method can cut the structure section into several parts according to flexible rules. The Figure 5(b) shows just one way, but not the only way, by which the cross section of the structure shown in Figure 4(b) is divided. The dimension of the divided parts can be adjusted to construct the project shown in Figure 4(b), according to the specific conditions of the project. Additionally, a new type of coupled rectangular pipe-jacking TBM is developed to meet the special needs of this project, which can be uncoupled into two independent pipe jacking machines, as shown in Figure 9.

2) Steel and RC composite box element
After the pipe-jacking of all the seven tunnels, the underground space will be formed by converting the tunnels into a whole framework structure. During the process of combination and conversion, temporary structures will be removed. This will be a huge waste of material. Therefore, a new type of pipe-jacking box element is developed to reduce the waste, which is composed of steel segments and precast RC segments. And the steel segments of the side wall can be dismantled and reused. The composite box element is shown in Figure 10.

![Figure 10. Combination of pipe segment (mm).](image1)

![Figure 11. Three types of nodes diagram.](image2)

(3) Joint processing

Three classes of joints should be processing properly during the construction of the underground parking project when using the CC method, as shown in Figure 11.

Joints of class A: joints between the precast reinforced concrete segments and the steel sidewall segments, which will be connected by bolts.

Joints of class B: joints between RC segments of two contiguous tunnels, which will be processed by cast-in-situ reinforced concrete after the connection of the rebar.

Joints of class C: joints between the precast RC segments and the permanent steel members installed afterward, which will be processed by bolt connection.

**Shortcomings and Improvement Measures**

The pilot project using CC construction method has already accomplished successfully. But there are still some difficulties and shortcomings during the construction of the project. As results of hard work and studies in the pilot project, corresponding solutions and improvement measures are developed as follows.

(1) The processing measure of class B joint

As shown in Figure 11, class B joints located between RC segments of two contiguous tunnels. The initially conceived processing measure of class B joints is illustrated in Figure 12. Because of the deviation and dislocation of the two adjacent tunnels during the actual pipe-jacking construction, the connecting rebars have to be shaped into too many different sizes that is hard for processing. And the space between the reinforced concrete segments of two adjacent tunnels is quite small. These reasons lead to many problems for the class B joints processing according to the initially conceived method.

![Figure 12. Class B node original handling measures.](image3)

To solve these problems, investigations relevant cases in China and abroad are made, and base on which the processing method of Class B joints is optimized. The optimization measures ensured efficient and reliable connection of the rebars, which are summarized as follows:

a) the reserved rebars and also the connecting rebars are properly bent within the scope of the design standards and specifications;

b) the Class A mechanical rebar connection measure is adopted;

c) the connection rebars of different dimensions are classified, counted and processed in batches.

(2) Overall-Carrying-Soil Effect
The action of overlaying soil moving forward during the pipejacking usually happens in shallow-buried rectangular pipe-jacking cases. To prevent the overlaying soil moving with the machine and the tube, friction reduction measures are taken in the experiment of CC method at the very beginning. The consideration for the action of the entire overlaying soil moving forward is insufficient, which led to a failure of the overlaying soil.

Focusing on this typical failure modus, the subject of Overall-Carrying-Soil Effect is proposed, and the numerical relationship between the parameters of the rectangular pipejacking and the failure of overlaying soil is finally achieved, which provides a theoretical support for the expansion of the CC method.\textsuperscript{[17]}

Expansion of CC Method

At preset, the attempt of the CC method on single-layer underground parking project has been proved successful. The improvement and optimization of the CC method and the summarization of the achievements are under proceeding. The method can not only be applied in single-layer underground parking projects, but also in many other large-scale underground projects in urban area.

Multi-layer Underground Spaces

Take large undrmetro stations as an example. The main feature of these project is long and narrow shaped, deep buried and cross-section fixed. Nowadays, the conventional cut-and-cover method is more and more difficult to apply in urban areas because of its affection to the environment. The CC method provide a better solution for the construction of these projects, as shown in Figure 14. Figure 14 (a) shows the standard cross section of a metro station, and (b) shows the conception of the way using CC method to construct a metro station by cutting the whole cross section into parts and converting the sequentially excavated parts into the final space.

![Figure 14](image)

(a) the standard cross section of metro station
(b) the initial construction program of CC method

Figure 14. Multi-story underground space development.

Long Distance and Curve-Shaped Underground Space

The pilot project adopted a straight pipe-jacking technique, which is not suitable for long distance and curve-shaped cases. But new techniques of shield TBM, such as rectangular TBM, quasi-rectangular TBM, horseshoe-shaped TBM, has already been developed and successfully used in some cases.
Shield TBM method can perfectly solve the problems in curved tunnel construction. And the CC method can also be used in curved underground projects by using shield TBMs. Therefore, it is feasible that the CC method will be further applied in the construction of curved underground spaces on the basis of the successful application in straight underground spaces, as shown in Figure 15. Figure 15(a) shows a curved section of utility tunnel. Figure 15(b) shows the cross section of the utility tunnel. Figure 15(c) illustrates the construction plan based on the CC method.

Irregular Cross Section Underground Space

Taking an integrated metro station as an example, this type of projects usually located in the core commercial area with irregular sections and cannot be simply excavated using conventional cut-and-cover method. The CC method provides a more practical solution for this type of projects, which is shown in Figure 16. Figure 16 (a) shows the standard cross section of a large integrated metro station, and Figure 16 (b) shows the solution based on CC method.

Summary

Under the special boundary conditions of the construction of large underground spaces in urban area, the requirements for the construction method are getting more and more strict. However, the conventional and unconventional construction methods all have their limitations at present. Based on the advantages of these methods, the mechanized structural cut-and-convert method, which is called CC method, was developed, and successfully applied in the pilot project of CREG Underground Parking. On the basis of the research and practice, conclusions are drawn as follows:

(1) The CC method, which integrates the advantages of conventional construction methods and unconventional construction methods, can primely adapt the construction environment of urban built-up areas, and also have great advantage in economic efficiency, risk control and construction speed.

(2) The “cut-convert” concept of underground structure, the steel and reinforced concrete segment composited pipe-jacking rectangular element, the new techniques of the joint processing measures and coupled pipe-jacking rectangular machine has all been proved to be practicable by the successful application of the CC method. The improvement measures of this method are also discussed in this paper.

(3) The boundary conditions of the parking project are relatively simple: single-layer structure with 6 spans, straight pipejacking, and soft soil without groundwater. Although the attempt of this
new method is successful, but deep research and developing work have to be done to make the method adapt to more complex and difficult conditions.

(4) The CC method has a good promotional value on the development of large underground space with multi-layer, curve-shape, long distance, fabrication and cast-in-place combined structure. This is also an important research direction in the next step.

The study of CC method aims at providing a safe and reasonable solution for the development of large-scale underground spaces in urban and especially the built-up area.

References

[1] Wang Wenzheng, Kong Heng, Han Xuegang. The Key Technology About Laying Fabricated Strap Method in Subway Station Construction[J]. Construction Technology, 2014(s2):129-135.

[2] Xu Jia-min. Preliminarily Discussion on Introduction of Laying Fabricated Strap Method to Construct Metro Station[J]. Journal of Railway Engineering Society, 2009, 26(9):90-92.

[3] Wang Mengshu. The Boring Excavation and Construction in Beijing Metro[J]. Chinese Journal Rock Mechanics and Engineering, 1989, 8(01):52-62.

[4] Wang Mengshu. An Investigation on Design and Construction of Shallow Cover Underground Excavation[J]. Underground Space, 1992(2):289-294.

[5] Design and Analysis of the Cover Structures for Supper-shallow-buried Underground Engineering Underneath Road[J]. Construction Technology, 2014(s1):349-353.

[6] Zhang Guoliang, Zhang Zhengang. Discussion on Construction of PBA Method in Single-story Large Span Submerged Subway Station[J]. Railway Engineering, 2005(3):38-40.

[7] Li Hao, Ge Ke-shu. I. Ground Surface Settlement Analysis in Metro Construction by PBA Method[J]. West-china Exploration Engineering, 2014, 26(11).

[8] Sato, Takuya, Minagawa, Kumbo, Furukawa, FAN. Construction of HEP & JES Construction Method (Mt. Oguda Bv, Omura Omoko Bv) [J]. Sed, 2000:96-99.

[9] Shimizu, Aya, Watanabe, Akino, Chiba, Kyosuke. Taken into account for the construction of mechanical construction under the line--HEP & JES method example (Special road and tunnel construction machinery)[J]. Construction Machinery & Equipment, 2003, 39:6-11.

[10] Chen Jiuheng. Construction Technique of Prefabricated Subway Station[J]. Railway Construction Technology, 2015(11), 62-69.

[11] Li Zhaoqing, Wang Chen, Su Huifeng, et. An experiment Study on the evolution law of concrete structure crack and joint seam deformation for tenon groove joints in the prefabricated metro station[J]. China Civil Engineering Journal, 2015(s1):409-413.

[12] Zhong Chun-ling, Li Lei. Exploration of Prefabricated Station[J]. Journal of Jilin Jianzhu University, 2015, 32(6):1-4.

[13] Liu Jian-hong. Study On The Design Optimization Of The Fabricated Structure Of The Subway Stationg Constructed By Open-Cut Method and the Mechnaical Behaviour of Construction[D]. Southwest Jiaotong University, 2017.

[14] Peng Limin, Wang Zhe, Ye Yichao, Yang Weichao. Technological Development and Research Status of Rectangular Pipe Jacking Method[J]. Tunnel Construction, 2015, 35(1):1-8.

[15] Zhang Jian-bin. Displacement Monitoring Analysis Of Xiamen Xiang’An Subsea Tunnel In Landside Section Constructed With Crd Method[J]. Chinese Journal Rock Mechanics and Engineering, 2007, 26(s2):3653-3658.
[16] Cui Xiao-peng, Sun Shao-feng, Wang Guang-hon, et. Comparison and Contrast between CRD Excavation Method and 3-benca 7-step Excavation Method and Their Optimization[J]. Tunnel Construction, 2010, 30(2):131-133.

[17] Gao Yi, Feng Chao-yuan, Cheng Peng. Study on the “Overall-Carrying-Soil Effect” of Shallow Buried Rectangular Pipe Jacking[J]. Chinese Journal of Geotechnical Engineering, 2018:1-6.