The design and construction of a large composite subway station in limited space: An exemplary application of OCUE method in Xuzhou, China

Junzuo He¹, Shaoming Liao¹,*, Zhiqun Gong²,³, Cong Tang¹, Mengbo Liu¹ and Yang Li²,³

¹ Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
² China Construction Infrastructure Co., Ltd, Beijing 100022, China
³ China Construction Eastern Investment Co., Ltd, Xuzhou 221005, China

Abstract. Due to the compact space and high utilization demands, the construction of large underground subway transfer station in urban area, like Pengcheng Square station in Xuzhou, China, was confronted with various obstacles, such as nearby surface and subsurface structures, heavy road traffic, and clay-rock mixed ground conditions. Based on careful investigations to all surrounding limitations, an innovative composite station form and its corresponding construction method, open cutting with underground excavation (OCUE) method, were introduced. The construction performance of this method has been confirmed by field monitoring. The main findings from the research include: (1) Sophisticated design and construction is essential for satisfying the expected functions of the station, minimizing the influence on the heavy traffic and sensitive structures in adjacent, as well as tackling the adversities of the clay-rock mixed strata; (2) Supported by the OCUE method, composite form of subway station was delicately designed to maximize the utilization of limited space, it comprised of open cutting part, underground excavation part and half-covered excavation part; (3) The implementation of OCUE method was successful with little influence on the surrounding traffic and buildings. Experiences obtained from this project can provide effective reference for similar cases.

Keywords: large composite subway station; limited space in urban area; clay-rock mixed strata; OCUE method

1. Background

As a new growing city located in the northwest of Jiangsu province (Figure 1), Xuzhou has witnessed a rapid development in economy and population during the last few decades. Similar to many other economically developed areas, Xuzhou is now making efforts to build a subway net and corresponding transfer stations for the purpose of alleviating the traffic problems above ground surface as well as promoting the further development of Xuzhou based on TOD mode [1].
However, considerable problems may take place while building such a large span deep underground structure in the center urban area of Xuzhou, where resident population and traffic flow are increasing at a rapid pace. Pengcheng Square station, a large transfer station for Metro Line 1 and Metro Line 2 situated underneath the juncture of the three center urban districts of Xuzhou (Figure 1), is a typical case. Under the extreme compact space limited by high-rise buildings, underground structures and arterial roads, adverse effects such as occupying much urban traffic land [2] and imposing threat to the structures in adjacent [3] will arise if open cutting method is adopted. Although underground excavation method could act as a good mean to minimize the influence of construction on the ground surface, high cost of time and money as well as difficulties in management keep it from large-scale application [4].

Hence, in this paper, taking the project of Pengcheng Square subway station in Xuzhou as an example, difficulties in constructing large subway transfer station in the center urban area of Xuzhou were investigated. A composite subway station form was proposed to cater the complicated circumstance around Pengcheng Square, and corresponding construction method nominated as open cutting with underground excavation (OCUE) method emerged recently for its high adaptability to various complex conditions [5]-[7] was applied. Last but not least, characteristics of the implementation of OCUE method in Xuzhou clay-rock mixed strata were studied to provide reference for similar cases.

![Figure 1. Geographical location of Xuzhou and the project site.](image)

### 2. Limited surface and subsurface conditions for Pengcheng Square station

#### 2.1. Dense buildings and underground structures
Since the Pengcheng Square station is located in the prosperous area of Xuzhou, numerous high raised buildings are around it (Figure 2). Among them, Sunning Square seated on the east side of the project, possesses one main tower with a height of 266 m (highest building in Xuzhou) and four sub towers with heights of 99.6 m. Comprised of high-grade office rooms, restaurants, department stores and apartments, Sunning square is the largest urban complex of Xuzhou. Sited on the west side, Pengcheng square, the largest urban square in Jiangsu province (250 m along east-west direction and 400 m along south-north direction) with a green land of over 42,000 m², has a great contribution to the cityscape and public leisure. In addition, buildings such as Fujing comprehensive building on the east side, Pengcheng hospital in the southeastern corner, Xuzhou Department Store in the southwestern corner also play important roles in the service of Xuzhou citizens’ urban life.

Besides buildings on ground surface, there are three large underground structures adjacent to the project: (1) the Central Fashion Avenue Underground Shopping Mall on the west side, (2) the Yovo...
Underground Shopping Mall and attached underground garage with 370 berths on the south side and (3) attached sunken plaza and basement of the Suning Square on the east side.

Taking the important function, complicated structure and large volume of the adjacent buildings into account, great price would be paid to demolish them for the construction of Pengcheng Square station. Thus, a sophisticated form of the station should be designed to make full utilization of the limited space. Meanwhile, owing to the short distance from the project site, additional inner force and deformation will inevitably take place and impose great threat to the buildings during the construction. So delicate construction program matching with the composite form of station should be planned to minimize the construction disturbance to the adjacent buildings.

![Diagram](image)

**Figure 2.** Layout of circumstance around project site.

### 2.2. Heavy traffic around the project site

Huaihai Road, approximately 4.3 km long and 30 m wide with 6 lanes in two directions, is one of the most important urban arterial roads in Xuzhou, connecting the whole downtown in east-west direction. Pengcheng Road, also having 6 lanes in two directions, is a famous historic and cultural street functioning as the central axis of Ancient Xuzhou.

Different methods were proposed to quantify the extent of traffic pressure, in this paper, traffic performance index (TPI) [8] obtained by weighting of different congestion state of each road based on the travel time and road grades is used. The standardized values of TPI range from 0 to 10 and are divided into four grades as presented in Table 1.

**Table 1.** The relationship between TPI value and traffic condition.

| Grade       | TPI      | Description                                                                 |
|-------------|----------|------------------------------------------------------------------------------|
| Severely congested | [0, 2.5) | More than extra 150% of normal travel time will be consumed on the road          |
| Congested    | [2.5, 5) | Extra 50%~100% of normal travel time will be consumed on the road               |
| Mildly impeded | [5, 7.5) | Extra 100%~150% of normal travel time will be consumed on the road             |
| Basically unimpeded | [7.5, 10] | Less than extra 50% of normal travel time will be consumed on the road         |
Based on the TPI, the historical traffic performance around the project site on July 20th, 2020 is revealed in Figure 3. The most congested periods were 7:35 am to 11:15 am and 5:45 pm to 7:10 pm, which were termed morning rush hour and evening rush hour respectively. In these periods, traffic condition deteriorated to mildly impeded and even congested. From the perspective of traffic condition around the project site at 8:30 am, it is clear that severe congestion took place on the Huaihai Road and Zhongshan Road which were around the project location. Hence, effective construction method should be taken to avoid road occupation, otherwise chaos and congestion of traffic might be resulted.

![Figure 3](image)

**Figure 3.** TPI time-history curve of Xuzhou on July 20th, 2020 and traffic condition around project site (Data sources: http://jiaotong.baidu.com/top/report/?citycode=316).

### 2.3. Complicated geological conditions

Figure 4 presents typical strata profile along with soil properties at the project site. Its ground comprised of 23 m thick superficial deposits underlain by decomposed bedrock. The superficial deposits were composed of (1) miscellaneous fill layer at 0~3 m below ground surface, (2) silty clay layer at the depth of 3~4 m, (3) old city miscellaneous fill of Xuzhou at the depth of 4~10 m, and (4) hard plastic clay layer at 10~23 m below ground surface. The underlying bedrock below the depth of 23 m consists of moderately weathered sandstone and limestone.

![Figure 4](image)

**Figure 4.** Strata information.

Unique characteristics could be found in the clay-rock mixed strata of Xuzhou which bring additional challenges to the project: (1) old city miscellaneous fill is a characteristic ground type of Xuzhou, which is very uneven, loose and easy to collapse; (2) saturated uniaxial compressive strength of sandstone and limestone can reach up to 130 MPa locally, which will lead to difficulty in the trenching for diaphragm wall; (3) clay-rock interface distributed in an inclined angle of 70~80° located around 23 m below...
ground surface may increases the possibilities of instability of tunnel face when conducting underground
evacuation by blasting; (4) high risk of water gushing owing to the presence of high pressure confined
aquifers in the bedrock with a water head about 6–8 m below ground surface.

3. A composite form of subway station designed to counteract the limitations

As far as the limited conditions concerned, sophisticated station form and corresponding construction
method should be designed to ensure the smooth conduction of the project. For comparison, several
methods to build subway station are shown in Table 2, each of which has its own features [9]-[10].
Apparently, conflict between cost and effect will arise when merely open cutting, covered excavation or
underground excavation is considered in the case of this project. In order to tackle this dilemma caused
by the defects of the traditional method, an improved excavation method is introduced, namely OCUE
(Open Cutting with Underground Excavation) method. Different from normal methods, OCUE method
has high flexibility for it can adopt different construction methods, sequences and structure forms to
meet various limited boundary conditions and diverse functional demands.

Based on the OCUE method, unique form of Pengcheng Square station is contrived to adapt the
limited conditions as depicted in Figure 5 and Figure 6. Two stations are combined with a L shaped
layout which can form a network with surrounding underground space through the two-way station with
a clear hierarchy and structure [11].

**Table 2.** Comparison of different methods in construction of large subway station in urban area.

| Effects               | Open cutting      | Covered excavation | Underground excavation | OCUE     |
|-----------------------|-------------------|---------------------|------------------------|----------|
| Time                  | Short             | Relatively long     | Long                   | Relatively long |
| Expense               | Low               | Relatively low      | High                   | Medium   |
| Environmental impact  | Big               | Medium              | Small                  | Small    |
| Ground disturbance    | Poor control      | Poor control        | Effective control      | Effective control |
| Construction safety   | High              | Relatively high     | Low                    | Medium   |
| Construction process  | Simple            | Relatively simple   | Complex                | Complex   |

**Figure 5.** Schematic graph of the configuration of Pengcheng Square station.

The whole transfer station can be separated into three main parts according to construction method:
left tunnel station combined with an external hanging hall for Metro Line 1 (part A), right tunnel station
for Metro Line 1 (part B) and station for Metro Line 2 (part C). Part A, arranged on the northern side of
Huaihai Road, is a 4-storey underground station constructed by open cutting method which can not only make full use of the remaining open space for reducing the cost of time and money but also provide assistance to the construction of part B. External hanging hall and sunken plaza is set for people flow evacuation, commercial use as well as harmonious coexistence of the station and Pengcheng Square. Part B is a single storey station arranged below Huaihai Road. In order to avoid disturbance to the traffic on Huaihai Road, underground excavation method is adopted in this part. 6 cross contact tunnels are built to connect the part B with part A. Two tunnels of Metro Line 1 are set to adequate depth so as to avoid the Fashion Avenue Underground Shopping Mall. Part C is arranged below Pengcheng Road between Pengcheng Square and Suning Square. Method of half-covered excavation is applied out of the consideration of minimizing the influence on Pengcheng Road. In addition, 15 entrances are set to enhance the connection between Pengcheng Square station and surrounding buildings.

Figure 6. Cross section of Pengcheng Square station and surrounding environment.

4. Application of OCUE Method in limited space

4.1. Construction program of OCUE method

Specific configurations of the OCUE method used in this project is depicted in Figure 7~Figure 9. Excavation pit for part A was in the form of pit in pit with a width of 58 m, an outer depth of 23 m and an inner depth of 31 m. Five layers of reinforced concrete struts and diaphragm walls were casted to support the excavation pit. Part C was a 162 m long, 23 m wide and 23 m deep rectangular pit supported by diaphragm walls and four layers struts, the first of which was concrete struts and the rest of which were steel tube struts. Part B was a group of short tunnels with a total length of 248 m. Among them, the right tunnel, part of left tunnel which extends out from the pit of part A, channel 1~channel 3 and channel 6 were constructed by CRD method, while channel 4 and channel 5 were constructed by bench cut method. Primary lining of shotcrete and cement grouted bolts as well as secondary lining of casted concrete were adopted to support the tunnels. Besides, advanced pipe roofing and pre-grouting small pipes were set up previously to pre-reinforced the ground.
Figure 7. Layout and construction sequence of the project.

Figure 8. Supporting system of excavation pit (Cross section 1-1 and 2-2 in Figure 7).

Figure 9. Cross section of tunnels: (a) Channel 1; (b) Channel 2; (c) Channel 3; (d) Tunnels for Metro Line 1; (e) Channel 4 and Channel 5; (f) Channel 6.
The following main sequential steps were implemented in this project: (1) construction of diaphragm walls and prefabricated concrete deck; (2) excavation of pits for part A and part C is conducted from two ends to intersection following the principle of stepped layered excavation and in-time installation of corresponding struts for each layer (S1~S8); (3) excavation of left tunnel for Metro Line 1 to extend out from the excavated pit (S9); (4) excavation of channel 1~channel 3 to extend out from the excavated pit (S10); (5) connection of channel 1~channel 3 to form the right tunnel for Metro Line 1 by excavation (S11); (6) connection of the excavated pit and the right tunnel by excavation (S12).

Additionally, in order to evaluate the ground disturbance induced by the implementation of OCUE method as well as to ensure the safety of surrounding structures, monitoring points were installed to measure lateral displacement of diaphragm walls (L1~L3) and settlement of ground surface (G1-1~G5-4). Layout of the selected monitoring points could be inferred from Figure 7. Diaphragm wall deflection and ground surface settlement should be controlled within 0.3% of the excavation depth (93 mm) and 0.25% of the excavation depth (78 mm) respectively.

4.2. Performance of OCUE method

Complying with the sophisticated program of OCUE method introduced above, construction of Pengcheng Square subway transfer station was executed smoothly without severe disturbance to the traffic and buildings around the site (as shown in Figure 10).

Cross section distributions of diaphragm walls deflections at L1~L3 and surface settlements at G1~G5 which were incurred by the construction are plotted in Figure 10. Under the combined effect of earth pressure and resistance provided by struts, deflection curves of diaphragm walls formed parabola shapes with peaks taking place between struts 3 and struts 4. The maximum lateral displacement at L1 and L2 were 32 mm and 35 mm respectively, while the maximum lateral displacement at L3 was significantly smaller (17 mm), which might be attributed to less disturbance and unloading in this section where the dimensions of inner pit and tunnel were relatively smaller. Owing to the ground movement resulted by deformation of diaphragm walls and excavation of tunnel group, each section of the ground surface settled in a shape of parabola. Maximum settlements ranged from 48 mm to 79 mm and occurred near the surface above the vault of right tunnel for Metro Line 1 (nearly 9 m away from diaphragm walls). Remarkably less settlement could be seen in the cross section of G1 because it was located on the boundary of the tunnel group. Both diaphragm wall deflections and surface settlements were controlled within requirements (93 mm and 78 mm respectively) in most of the monitoring points.

For further exploration, composition of deformations induced by OCUE method at each monitoring point is described by stacking bar in Figure 12. It could be found that, lateral displacement induced by
the open cutting of pit was predominant (82% of total lateral displacement in average) in the composition of diaphragm wall deflection, while in the composition of ground surface deformation, settlement caused by the underground excavation of tunnel group accounted for a larger proportion (72% of total settlement in average). Therefore, it was reasonable to deem that underground excavation conducted after the open cutting had subtle impact on the lateral wall but could increase the surface settlement substantially.

![Typical deformation distributions along different sections cross section.](image)

**Figure 11.** Typical deformation distributions along different sections cross section.

![Compositions of deformations: (a) diaphragm wall deflections; (b) ground settlements.](image)

**Figure 12.** Compositions of deformations: (a) diaphragm wall deflections; (b) ground settlements.

5. Conclusions

In this paper, the demands, merits and implementation of the OCUE method were thoroughly investigated through a case study of the design and construction of a large subway transfer station in urban area of Xuzhou. Main conclusions can be drawn as following:

(1) As a large subway station being located in the urban area of Xuzhou, Pengcheng Square station is surrounded by several arterial roads, high raised buildings as well as underground structures, so space remained for construction was extremely limited. Complicated characteristics of local clay-rock mixed strata also heighten the requirements of construction. Thus, comprehensive considerations should be taken in the design and construction of this station to fit the limited conditions.

(2) On the premise of OCUE method which combines the merits of traditional methods, Pengcheng Square station was delicately designed in a composite form. Open cutting for station of Metro Line 1 left tunnel and external hanging hall was conducted in the remaining limited open space. Station of Metro Line 1 right tunnel and corresponding cross contact tunnels were formed by tunnel group extended out from the open excavated pit by underground excavation method so as to avoid disturbing
on the arterial road above. Station of Metro Line 2 was constructed by half-covered excavation method which could recover the ground traffic as soon as possible.

(3) According to the field measurements, maximum deformations of diaphragm wall and ground surface were controlled within 31 mm and 22 mm respectively during open cutting, while reached up to 35 mm and 79 mm respectively after the underground excavation of tunnel group. Safety was confirmed since deformation was controlled within requirements in most of the monitoring points.

Although the planning of this subway transfer station in urban area is a local problem dependent on local service requirements, it could be expected that the application and promotion of OCUE method will grow continually in urban area for its high flexibility.

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