Study on Reasonable Combination of Retaining Structure and Main Structure for Tunnel Shaft in the Offshore Environment

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Abstract. Through the investigation, the design of the combination of the retaining structure and the main structure of the large-diameter shield shaft was summarized. Combined with the characteristics of the offshore shaft, considering the difficulty in implementing underwater pouring of high-grade underground diaphragm wall, through reasonably analyzing the characteristics of chloride environmental corrosion, a reasonable solution of supporting the temporary diaphragm wall to participate in anti-floating action is proposed. For the strictness of crack control in the chloride environment, it is proposed to use the frame beam as the purlins in the excavation stage, and the waterproof problem of the construction joint is better solved. Finally, the three-dimensional calculation results confirm the stress of lining wall is reasonable.

1. Foreword
With the development of urban construction, large underground projects such as super high-rise building basements, subway stations and tunnels, and urban road tunnels have emerged, and a large number of deep foundation pit projects have followed. For deep foundation pit, the underground diaphragm wall is the most widely used retaining structure, while its cost is higher. In order to reduce the cost, the underground diaphragm wall and purlins are also designed as permanent structures in many projects. This kind of structures are always called dual-purpose structure in China.

Dial-purpose diaphragm wall was widely used in the deep foundation pit of super high-rise buildings especially in Shanghai. Wang W.D. conducted a large number of technical studies on the dial-purpose diaphragm wall, and considered that the dial-purpose diaphragm wall has a very significant technical and economic effect as a kind of retaining structure integrating the retaining earth, water stopping, anti-seepage and the external wall of the basement structure[1]-[2]. However, Xu X.H. proposed that the dial-purpose diaphragm wall is difficult to construct, the construction quality is not easy to guarantee, and there are many weak links, which are easy to leak water[3]. He also summed up that dial-purpose diaphragm wall is adopted in Shanghai while single-purpose diaphragm wall is adopted in Northern area in China.

Based on the engineering practice of offshore tunnels, this paper proposes a new design concept and scheme for the retaining structure that adapts to the offshore chloride environment through engineering analogy and theoretical research. It is expected to better take into account the advantages of traditional dial-purpose diaphragm wall and single-purpose diaphragm walls.

2. Project overview

2.1. Project background
Responding to national strategy “Belt and Road Portal”, the road tunnel under the river Karnaphuli in Chittagong of Bangladesh was invested by China, and construction standards adopt Chinese standards. This is the first application of the Chinese standard in foreign tunnel project and has taken an important step towards the internationalization of Chinese standard.

Road tunnel under the river Karnaphuli is expressway which is 4 lanes carriageway with the speed of 80 km/h. The total length of the project is 9293m while the tunnel is 2925m. The tunnel shaft studied in this paper is located to the west of the river Karnaphuli, which consists of the superstructure and substructure. In the construction period, only the main frame structure of the substructure will be constructed for launching and receiving the tunnel shield. In the operation period, both superstructure and substructure will be used for vehicle travelling, tunnel ventilation, escape and rescue and housing of key equipment. The plane overall dimensions of the shaft are 48.7m × 25.0m and the field leveling elevation is +2.3m during construction, while the ground elevation is +4.74m, and the elevation of the bottom plate is -19.1m in the operation period.

2.2. Engineering geology
The engineering geology strata of the soil strata in this region is divided into 4 layers and then subdivided into several sub-layers according to the lithological characteristics and physical-mechanical properties. The excavation area of the foundation pit is mainly composed of sand and clay alternately while the bottom of the pit is mainly composed of dense and fine sand. The specific distribution of soil layers are shown in Figure 2 and the TBH16 revealed the thickest layer of clay. The main physical and mechanical parameters related to the design and calculation are shown in Table 1.
Table 1. The main physical and mechanical parameters.

| Stratum | Density $\rho$ (kg/m$^3$) | Cohesive force $c$ (kPa) | Friction angle $\varphi$ (°) | Lateral pressure coefficient $\xi$ | Coefficient of foundation bed $k$ (MPa/m) |
|---------|--------------------------|--------------------------|-----------------------------|-------------------------------|---------------------------------------|
| ③1     | 1.89                     | 11.2                     | 5.2                         | 0.53                          | 12                                    |
| ③2     | 1.95                     | 5.4                      | 31.1                        | 0.43                          | 8                                     |
| ③3     | 1.85                     | 5.2                      | 3.0                         | 0.53                          | 8                                     |
| ③4     | 1.95                     | 4.8                      | 31.6                        | 0.43                          | 15                                    |
| ③5     | 1.83                     | 8.2                      | 4.5                         | 0.53                          | 8                                     |
| ③6     | 1.96                     | 4.6                      | 32.7                        | 0.41                          | 20                                    |
| ③7     | 1.81                     | 12.6                     | 4.3                         | 0.35                          | 10                                    |
| ③8     | 2.05                     | 4.6                      | 33.5                        | 0.40                          | 25                                    |
| ④      | 2.00                     | 4.0                      | 35.0                        | 0.40                          | 35                                    |

2.3. Hydrogeological condition
The climate of River Karnaphuli area is typical dry season and rainy season climate with abundant rainfall in rainy season. The rainfall intensity is large and rainfall time is long. With the influence of seasonal rainfall, the water content in surface cohesive soil layer and the groundwater level varies greatly, and the phreatic water level also changes greatly. The phreatic water mainly occurs in the upper cohesive soil layer with a thickness of 1~5m.

Below the surface layer, the sand and clay are usually interbedded (See Figure 2). The confined water is mainly recharged by River Karnaphuli and sea water. The stratum is cut by River Karnaphuli and the sand layers have good water permeability, so the sand layer connect well with river. In addition, the west shaft is only 280m from the shore, so the groundwater is greatly recharged by the tidewater, which can be reflected from the pumping test of TBH17 hole.

3. Durability design for structures
3.1. Evaluation on corrosivity of water and soil
When the concrete structure is partially above the groundwater level and partially below the groundwater level, the soil sample and the water sample should be taken separately for corrosion test[4]. According to the testing and analysis of samples, the concentration of CL$^-\cdot$ in groundwater varies 4980~6420 mg/L and the concentration of CL$^-\cdot$ in soil varies 440~476 mg/kg. The corrosion level can be determined according to Chinese code[4].

Table 2. The corrosion level.

| Evaluation type | Corrosion of groundwater | Corrosion of soil |
|-----------------|--------------------------|--------------------|
| Corrosion on concrete structure by type of environment | Weak corrosive | Slight corrosive |
| Corrosion on concrete structure by permeability | Strong corrosive | Slight corrosive |
| Corrosion on reinforcement of concrete structures under long-term water immersion conditions | Slight corrosive | Weak corrosive |
| Corrosion on reinforcement of concrete structures under dry and wet alternate conditions | Strong corrosive | Weak corrosive |
3.2. Selection of structural materials based on durability

In ocean and offshore areas, reinforced concrete structures that contacting seawater chloride shall be designed with durability according to ocean chloride environment[5]. The lining wall of the shaft is exposed to the soil containing high sea water on one side and the air on one side. so the differences of local environmental effect level should be taken attention. In general, when underground structure use waterproof rather than drainage, it can be considered that there is no flow of water and air between the inner and outer sides of the lining wall. The design service life of structure is 100 years, but it is difficult to ensure that the waterproof material can service for 100 years while the fact is that most of the tunnels have water seepage or leak problem during construction and operation period. For inner side of lining wall, leaking water will cause an environment of dry and wet alternate condition and environmental effect level can be considered to be IIIE. For outer side of lining wall, insufficient of air makes it difficult to carbonize and corrode and environment action level can be considered to be IIID. Considering the higher environment action level of IIIE, concrete strength grade of permanent structure should not be less than C50 according to the Chinese Code.

When retaining structure is designed to be temporary structure, durability will not be considered and concrete strength grade could be C35.

3.3. Crack control standard

Varied environment action level have varied crack control standard, and the inner and outer side of lining wall can be designed respectively. For the tunnel projects built in the early years in China, the environment inside the tunnel was considered to be a dry environment and calculate width limitation of surface crack was 0.3mm. For this project, the width limitation of inner and outer side of lining wall are 0.15mm and 0.2mm respectively.

4. Study on retaining structure design cases of tunnel shaft

The retaining structure design of large-diameter shield tunnel shaft was researched about an important point that whether the retaining structure such as underground diaphragm wall and purlin was also used as permanent structure.

| Project name | Depth of foundation (m) | Thickness of underground diaphragm wall (m) | Thickness of lining wall (m) | Extra function of underground diaphragm wall | Extra function of purlin |
|--------------|------------------------|---------------------------------|----------------|---------------------------------|----------------|
| Shanghai Yangtze River tunnel - Pudong shaft | 23.66 | 1.0 | 1.2 | Permanent structure | Partial permanent structure |
| Shanghai Yangtze River tunnel - Changxing Island shaft | 24.7 | 1.0 | 1.2 | Permanent structure | Partial permanent structure |
| Nanjing Changjiang tunnel - Jiangbei shaft | 22.95 | 1.0 | 1.2 | Permanent structure | |
| Nanjing Yangtze River tunnel - Jiangbei shaft | 25.34 | 1.2 | 1.0 | Permanent structure | |
| Nanjing Yangtze River tunnel - Jiangnan shaft | 29.3 | 1.2 | 1.2 | Permanent structure | |
| Qingchun road tunnel - Jiangnan shaft | 29.4 | 1.2 | 1.2 | Permanent structure | |
| Qianjiang river tunel - Jiangbei shaft | 27.3 | 1.2 | 1.2 | Permanent structure | |
Most of the projects above use underground diaphragm wall as a part of lining wall and the others just use it as retaining structure without bearing capacity and anti-floating function. Especially the south bank shaft of Shantou bay tunnel have an offshore environment. C30 concrete was used for temporary diaphragm wall while C50 concrete was used for permanent lining wall.

All projects above use purlin as permanent frame-beam structure no matter whether diaphragm wall was permanent structure. However, there are differences at two points: 1) some projects just choose several important and large purlins as permanent structure to reduce construction joints between purlins and lining wall; 2) some projects use inverted construction to reduce construction joints, which means that the purlin and lining wall above the purlin would be pouring together[10]. It is worth noting that inverted pouring lining wall could be make sense unless the diaphragm wall was permanent structure.

### 5. Reasonable combination of underground diaphragm wall and lining wall

#### 5.1. Technical difficulties in chloride environment

If underground diaphragm wall is used as a part of lining wall, the concrete should be C50. Then the pouring and chipping of concrete will be difficulties. If underground diaphragm wall is used just as retaining structure, the anti-floating and crack control will be difficulties.

##### 5.1.1. Pouring high-grade concrete underwater.

At present, there are very few cases in which high-grade diaphragm wall were poured. It requires typical research and test to make sure the durability and costs a lot of time and money apparently. Moreover, the diaphragm wall below the foundation bottom have no effect at all during operation period.

##### 5.1.2. Chipping high-grade diaphragm wall.

Before launching of shield machine, the diaphragm wall in the portal area should be chipping by drills and cutters of shield. High-grade concrete can cause great damage to the cutters.

##### 5.1.3. High anti-floating design standard.

For operation period, anti-floating design water level shall be considered as 4.68m per the maximum 100-year tidal water level. The checking of limit state shall be conducted under two short-term conditions: 100-year flood level of 6.8m and 2.3m with seismic action respectively.

##### 5.1.4. Crack control of lining wall.

During the construction of the shield, the diaphragm wall can bear the earth pressure, while the lining wall needs to bear the earth pressure and water pressure and meet the requirement of crack control within 0.15mm.

| Project                        | Length (m) | Inner Width (m) | Outer Width (m) | Retaining Structure | Type of Structure |
|--------------------------------|------------|-----------------|-----------------|---------------------|-------------------|
| Shantou bay tunnel - South bank shaft | 29.6      | 1.2             | 1.2             | no                  | Partial permanent structure |
| Changjiangxi road tunnel - Puxi shaft | 33.65     | 1.2             | unknown         | Permanent structure  | Partial permanent structure |
| Heyan road tunnel - Baguazhou shaft | 26.7      | 1.0             | 1.2             | no                  | Partial permanent structure |
| Heyan road tunnel - Jiangnan shaft | 47.0      | 1.5             | 1.5             | no                  | Permanent structure |
| Jiajiang tunnel - Meizizhou shaft  | 25.6      | 1.2             | 1.2             | no                  | Permanent structure |
5.2. Reasonable use of underground diaphragm wall
The feasibility and risk brought by high-grade underwater concrete is difficult to control, so temporary diaphragm wall was chosen to be the study direction. There is a mindset that temporary structure cannot participate in anti-floating and lots of uplift piles will be required to solve the problem of anti-floating. For this shaft, it means 14 piles with a diameter of 1.2m and a length of 30m.

However, the diaphragm wall involved in anti-floating only needs to use its own weight just as the soil above the top plate. When diaphragm wall is considered as temporary structure, it is separated from lining wall and is immersed in soil and water so that have a better environment than dry and wet alternate condition. The corrosion of steel by chloride ions is difficult to control, but it is small corrosive to concrete\[5\]. Moreover, insufficient of CO\(_2\) makes it difficult to carbonize the concrete. So, it is reasonable to use the weight of diaphragm wall for anti-floating.

In order to transfer the weight of diaphragm wall to the lining wall, the traditional approach is using steel bars as a connection, which is not sufficient for durability under corrosive conditions. Three-turn shear slots were set around the shaft to solve the problem in this project. The lowest shear slot was set above the fifth frame beam and the weight of the diaphragm wall above the lowest shear slot could be considered for anti-floating calculation.

![Figure 3. Shear slots set between the diaphragm wall and lining wall.](image)

5.3. Anti-floating calculation
The anti-floating action shall be the combination of the load standard values, including the weight of diaphragm wall 22190kN, the weight of main structure 233029kN, the weight of the backfill 13534kN and uplift piles 10630kN (also column pile). The whole anti-floating action force is 279383kN, and anti-floating safety coefficient was calculated in the following tables which can all meet the limit requirement.

|                        | Design | Verification 1 | Verification 2 |
|------------------------|--------|----------------|----------------|
| Water level (m)        | 4.68   | 6.8            | 2.3            |
| Buoyant force (kN)     | 255421 | 278192         | 229857         |
| Safety coefficient     | 1.094  | 1.004          | 1.215          |
| Safety coefficient limit| 1.05  | 1.00           | 1.00           |

6. Reasonable combination of purlins and main structure

6.1. Influence of crack width limit on the reinforcement amount
The bending moment of the lining wall is about 1000-3000kN. The influence of the crack width limit on the reinforcement amount will be analyzed in Figure 4. Because of the influence of the chloride environment, reinforcement of the structure is increased by 7% to 20%, and the larger the bending moment, the greater the increase in the reinforcement amount.
6.2. Reasonable use of frame beam
The most unfavorable condition of shield tunnel shaft is to completely remove the support that influencing the launching and receiving of shield machine. Under this condition, the shaft is mainly resistant to horizontal loads by the lining wall and frame beam. The frame beam is the same as the concrete purlins, but it is much larger in size. The use of frame beams as purlins in the excavation stage has many advantages: 1) improve the rigidity of the retaining structure; 2) reduce the construction process; 3) reduce deformation and stress; 4) reduce the construction risk; 5) save the time and cost. However, the significant problem is waterproof of construction joint between frame beam and lining wall.

6.3. Waterproofing measures
The grade of waterproofing is grade 2 and one or two measures should be used for waterproofing of construction joint according to Chinese code. For this shaft, four measures were used: 1) back rubber waterstop; 2) cement-based permeable capillary crystalline waterproofing coating; 3) water-swelling waterstop; 4) grouting pipe. When some measures fail, grouting pipe embedded can be use to grouting to seal the seepage point. Shear bar was set to support the frame beam during excavation stage and it must ensure a clearance of 70mm or more from the reinforcement of frame beam.

6.4. Three-dimensional numerical calculation
The 3D finite element load structure model is used for calculating the main frame structure of the underground structure such as the frame beam and lining wall during construction and operation.
period. The following four conditions are mainly concerned: condition 1: complete the construction of the bottom plate, lining wall and remove the supports; condition 2: bore on the shield side before launching at the left line; condition 3: bore on the shield side before receiving at the right line; condition 4: conditions in the operation period.

The calculation results show that under the constraint of the five frame beams, the maximum bending moment design value of the inner side of the lining wall is 2669kNm, and the calculated crack width is 0.146mm with two rows of rebars of 32@100; the maximum bending moment design value of the outer side of the lining wall is 2725kNm, and the calculated crack width is 0.195mm with two rows of rebars of 32@100.

7. conclusion and suggestion
The combination of the retaining structure and the main structure needs to be determined according to the specific project characteristics. For example, although the dial-purpose diaphragm wall has many advantages, it is difficult to implement the underwater pouring of the high-grade diaphragm wall in the offshore environment. So the underground diaphragm wall is difficult to design as a permanent structure. Although the temporary diaphragm wall can not be used to bear water and soil pressure, it can still break the mindset and take measures to make the diaphragm wall play a greater role.
Combined with the shaft of road tunnel under the river Karnaphuli, through reasonable analysis and exploration, the following conclusions are obtained:

1) By setting shear slots between the underground diaphragm wall and the lining wall, the temporary wall structure can be used to resist floating.

2) By using the frame beam as the purlins in the excavation stage, the stress of lining wall will be reasonable.

3) By using more waterproofing measures, the waterproof effect of the construction joint is proved to be good according to the feedback of construction site.

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References
[1] Song, Q.J., Wang, W.D., Weng, Q.P.(2006) Design of dual-purpose diaphragm walls in deep foundation pits. Geotechnical Engineering., 28: 1590-1595.
[2] Wang, W.D., Weng, Q.P.(2005) Some Key Techniques for the Design of Dual-purpose Diaphragm Wall. Underground Space and Engineering., 1: 574-578.
[3] Xu, X.H.(2005) Comparison and Selection of Dial-purpose Diaphragm Wall and Single-purpose Diaphragm Wall for Open-cut Subway Stations. Railway Standard Design., 2005(12): 77-80.
[4] Ministry of Housing and Urban-Rural Development of People’s Republic of China.(2009) GB 50021-2001 Code for investigation of geotechnical engineering (Rev2009). China Building Industry Press, Beijing.
[5] Ministry of Housing and Urban-Rural Development of People’s Republic of China.(2008) GB/T 50476-2008 Code for durability design of concrete structures. China Building Industry Press, Beijing.
[6] Zhu, D.J., Zhao, Y.P., Shang, J.H., Zhang, Y.(2008) Deformation and stability analysis of foundation pit on Changxing Island. Geotechnical Engineering., 30: 100-104.
[7] Chao, W.H., Shen, W.Q.(2010) Super-large Shield Tunnel Engineering Design. China Building Industry Press, Beijing.
[8] Ning, M.Q., Xu, J.L.(2009) Analysis of Nanjing Changjiang Tunnel Shield Launching Shaft Structure. Railway Standard Design., 2009(6): 102-105.
[9] Zhang, X.C., Gong X.N, Yin, X.Y., Zhao, Y.B.(2011) Monitoring analysis of retaining structures for Jiangnan foundation pit of Qingchun road river-crossing tunnel in Hangzhou. Rock and Soil Mechanics., 32: 488-537.
[10] Zheng, G.P., Li, W.P., Zhang, D., Tang, Y.(2011) . Overview on Structure Design and Construction Technology of Qiantang River Tunnel North Working Shaft. Highway., 2011(8): 271-276.
[11] Fu, L.X., Wang, H.L., Jiang, Z.H.(2018) Study on the Stress and Deformation Behaviors of a Deep and Irregular Foundation Pit as the Shield Launching Shaft in a Sea Reclaimed Cofferdam. Modern Tunneling Technology., 55: 133-139.
[12] Zhang, H.(2011) Outline of Structural Design of Puxi Shaft in Construction Stage of Shanghai Changjiangxi Road Tunnel. Underground Engineering and Tunnels., 2011(4): 16-19.