1. Introduction and Engineering Situation

Haicang Tunnel of Xiamen is the third submarine tunnel using drilling and blasting method in China as well as the major part of the east-west corridor of Xiamen City, which connects the Huli District in Xiamen downtown and Haicang District in Xiamen suburb. The tunnel is constructed according to the first class highway standard, and the design speed is 80km/h. Besides, it’s designed with double-way six lanes and designed service life of 100 years under normal operation.

A ventilation tower of Haicang Tunnel is designed in Xiangyu free trade zone in Xiamen downtown, which consists of an air inlet shaft and air outlet shaft in the lower part and a building in the upper part. The ventilation tower basement excavation is built in the second phase. The depths of No.2 shaft pit, No.3 shaft pit and the main pit are 21m, 28m and 15.9m. The excavation area of the foundation pit is about 1770m$^2$ and the perimeter is about 188m.

2. Engineering Geology and Hydrogeology

The foundation pit is located in the denuded and residual hilly area with artificially backfilled soil widespread. The terrain is relatively flat and the groundwater level is obviously affected by the tide. The most unfavourable working condition is taken into consideration by setting the design groundwater level to be flush with the ground.

28509m geophysical prospecting works, 1700m offshore and inshore geological drillings, 132 times in-situ tests and 82 times laboratory tests were carried out for data acquisition. According to the geological exploration results, the recommended values of parameters are listed as follows:
Table 1. Recommended values of parameters

| soil stratum code | soil stratum name                      | gravity density (kN/m$^3$) | cohesion (kPa) | friction (°) | coefficient of permeability (m/d) |
|-------------------|----------------------------------------|-----------------------------|----------------|-------------|----------------------------------|
| ①①                | miscellaneous fill                     | 18.0                        | 12             | 15          | 20                               |
| ②①                | silt                                    | 16.0                        | 10             | 2           | 0.01                             |
| ②②                | medium coarse sand                      | 19.0                        | 0              | 32          | 30                               |
| ②③                | silty clay                              | 19.0                        | 30             | 13          | 0.05                             |
| ③                  | residual gravelly clay                  | 19.4                        | 25             | 22          | 0.5                              |
| ⑤①                | completely decomposed granite sand      | 18.9                        | 28             | 25          | 0.06                             |
| ⑤②-1              | strongly weathered granite sand         | 21.0                        | 30             | 30          | 0.08                             |
| ⑤②-2              | fragmentary strongly weathered granite | 22.0                        | (30)           | (30)        | 5                                |
| ⑤③                | moderately weathered granite            | 26.1                        | (50)           | (32)        | 3                                |
| ⑤④                | slightly weathered granite              | 27.2                        | (90)           | (35)        | 1                                |

Annotations: value in square brackets represents rock mass equivalent internal friction angle, while that in parentheses represents shear resistance index of structural plane.

3. Surrounding Environment
The foundation pit is located at Xiangyu free trade zone in Xiamen downtown, Yinheng building to the east, Gangzhong Road in the west, Yunan No.1 Road in the north and Yunan No.2 Road in the south. The minimum distance between the outer side of the excavation and the edge of the Yinheng building is about 18m. There are six kinds of underground pipelines around, including rainwater, telecommunication, street lamp, sewage, power and water supply.

![Excavation plan and surrounding conditions](image-url)
4. Foundation Pit Support Design before Scheme Variation

Combined with the excavation depth, surrounding environment and engineering hydrogeological conditions of the foundation pit, it is determined that the importance level of the excavation project is level one. The structure service life of the foundation pit is two years. The ground overload of the general section is taken as 20kpa and the building load is taken as 15kpa per layer[1-2].

According to the drilling location, stratum parameters, excavation depth, surrounding load and construction stage, the foundation pit is divided into eight sections. The structural stress and foundation pit stability are checked by unit calculation module of the deep foundation pit of Leading Software. The original design parameters of each support section are as follows.

| Section code | Section length(m) | Excavation depth(m) | Designing pile length/m | Anchor information |
|--------------|-------------------|---------------------|-------------------------|-------------------|
| FABC         | 39.73             | 28.0                | 30.0                    | The excavation depth using normal construction method is 15.7m with four-layer steel support, while the rest of the excavation is designed to be carried out by reverse construction method. |
| CDEF         | 41.47             | 28.0                | 22.5                    | five-layer reinforced concrete support |
| LKJI         | 40.14             | 20.9                | 20.7                    | |
| IHML         | 41.06             | 20.9                | 23.0                    | |
| CQ           | 15.87             | 15.9                | 21.5                    | |
| QPO          | 39.10             | 15.9                | 19.5                    | |
| ONK          | 30.91             | 15.9                | 20.0                    | |
| GE           | 15.38             | 15.9                | 20.5                    | |

Considering the influence of underground water, the boundary between opencut-and-cover method and subsurface excavation of the foundation pit is determined by the whole section entering into the medium to slightly weathered surrounding rock.

Sleeve valve pipes and high-pressure jet grouting piles are used for water sealing between piles. Besides, two rows of occluded high-pressure jet grouting piles are additionally set on the side near Yinsheng building for water separation treatment. φ1200@1400 bored piles are used for the retaining piles of the foundation pit and φ600 high-pressure jet grouting piles are applied for the water sealing between piles. Typical cross-section of foundation pit in the original design is illustrated in Figure.2.

5. Foundation Pit Support Design after Scheme Variation

In the original design, No.2 shaft and No.3 shaft are excavated to 15.7m by normal construction method in the first phase of the foundation pit and the main structure is built back to the ground afterwards. Then the underground second floor slab, the first and second rib beams, the structural bottom plate and the side wall are built by reverse construction method.

According to the construction progress in site, retaining piles and water stopping measures has been completed already. Meanwhile the shaft has been excavated to the interface of opencut-and-cover method and the subsurface excavation method. Due to the influence of the overall construction progress of the tunnel, the original design can no longer meet the requirements of helping construction of the main tunnel. So it is necessary to adjust the excavation sequence to run through the shaft as soon as possible.

Therefore, the reverse construction part is cancelled and the normal construction method is applied exactly to the interface of open and subsurface excavation. In the meanwhile, the main structure is built back to the ground. At this time, it reveals that the excavation depth of CDEF and LKJI section of the excavation is greater than that of the completed retaining pile, resulting in the retaining pile hanging above the bottom of the foundation pit.

In order to ensure the structural safety during the later excavation, the original No.3 shaft support scheme is adjusted as follows:
When the shaft is excavated to the depth of 15.7m, the 2nd basement slab shall be constructed first. And then it shall be rigidly connected to the retaining pile through planting reinforcing bars.

After the completion of the construction of the 2nd basement slab, two Φ609×16mm steel support will be installed in the same plane position as the upper steel support.

At this time, the upper foundation pit has been in a stable state. Therefore, the construction can be carried out after the completion of the vertical mucking lifting function of the shaft.

During the excavation of the original reverse excavation section, I20b joist steel is added, considering the pile foundation is placed outside and not affecting the thickness of the main structure’s inner lining wall of 1m. Double layer Φ8@20×20cm steel mesh, 25cm thick C25 shotcrete as well as 3m long Φ42×3.5mm small pre-grouting pipes @140×75cm as the primary support. Seven layers and six double splicing I45b joist steel are set as the internal support with vertical layer spacing of 1.5m, whose surface position are the same as the upper steel supports.

The lining of the original reverse excavation section can be constructed in sections from the bottom to the top after the excavation of the shaft and the vertical mucking of the main tunnel are completed.

No.2 shaft is similar to No.3 shaft in the excavation support scheme. Two layers of I45b joist steel are sufficient for No.2 shaft as the excavation depth is smaller.

Taking No.3 shaft foundation pit as an example, the calculation method of the changed structure is described as follows:

In the depth between 0 to 15.7m, the foundation pit stability is checked by Leading Software. At this time, the construction of the 2nd basement slab is already completed. Therefore the upper part of the foundation pit is in a safe and stable state.

In the depth between 15.7 to 28.0m, the Rankine’s earth pressure theory is applied to calculate the earth pressure at the boundary between the opencut-and-cover section and subsurface section[3].
The original retaining pile is used as advanced support in the concealed excavation theory, while the physical and mechanical parameters of surrounding rock are initiatively and properly improved [4]. The internal force of the double I45b joist steel structure and the overall deformation of the foundation pit are calculated by ANSYS.

According to the monitoring data, the deformation of the retaining piles and that of the shaft foundation pit are small and acceptable, and the pit is in a safe and stable state. At present, No.2 shaft and No.3 shaft excavations have been finished and filled back, and the foundation pit of the second phase ventilation tower basement is under construction.

6. Conclusion and Prospect

In order to speed up the construction progress and guarantee the construction period, the original combined construction scheme of No.2 and No.3 shaft excavations using opencut-and-cover method and subsurface method is changed into the opencut-and-cover method only, resulting in insufficient embedded depth of the constructed retaining pile which is in the state of suspension.

At this time, the 2nd basement slab is constructed to ensure the stability of the upper foundation pit. Under the premise of ensuring the stability of the upper foundation pit, the constructed retaining pile at the lower part is taken as advanced support. The newly constructed shotcrete anchor support and internal steel support at the lower part are also effective. The measured data of foundation pit excavation turn out to be stable, which shows that the changed scheme is useful and feasible.

Result reveals that this method can effectively maintain the safety and stability of the shaft foundation pit although, the actual improvement effect of the built retaining pile on the surrounding rock and soil parameters is difficult to quantify precisely. In the practical engineering application, all parties involved in the construction shall carefully study the design scheme before construction. If it has to be changed in the end, the excavation scheme shall be defined as early as possible to avoid the hanging state of the retaining pile.

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