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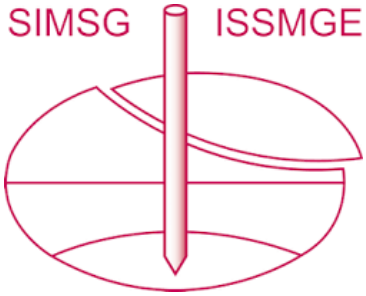

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Overview of Shanghai Yangtze River Tunnel Project

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ABSTRACT: In the paper, an introduction of the construction background and scale of Shanghai Yangtze River Tunnel and Bridge Project and natural conditions of Shanghai Yangtze River Tunnel construction are given. The overall design concept and some critical technical solutions such as segment structure of large diameter bored tunnel, water proofing of segment under high depth and water pressure, long tunnel ventilation system and fire fighting system are described. Characteristics of two mixed TBM with a diameter of 15,430 mm are described. The overall construction methods of tunnel, and critical technical solutions and risk provision measures for large and long river-crossing tunnel such as the front surface stability for bored tunnel construction, floating resistance of large diameter tunnel, long distance construction survey, synchronous construction of internal structure, and cross passage construction of fresh/salty alternating geological/environmental condition are discussed.

1 INTRODUCTION

Shanghai Yangtze River Tunnel and Bridge project is located at the South Channel waterway and North Channel waterway of Yangtze River mouth in the northeast of Shanghai, which is a significant part of national expressway, as shown in Figure 1. It is an extremely major transport infrastructure project at seashore area in China at Yangtze River mouth and also the largest tunnel and bridge combination project worldwide. The completion of the project will further promote the development space for Shanghai, improve the structure and layout of Shanghai traffic system, develop resources on Chongming Island, accelerate economic development in the north of Jiangsu Province, increase the economy capacity of Pudong, accelerate the economy integrity of Yangtze River Delta, boom the economic development of Yangtze River area and even the whole country and upgrade the comprehensive competence of Shanghai in China and even in the global economy.

Shanghai Yangtze River Tunnel and Bridge (Chongming Crossing) alignment solution is the planned western solution which is implemented firstly based on the Shanghai overall urban planning, and comparison between east and west alignment and in combination of various aspects. The western alignment starts from Wuhaogou in Pudong, crossing Yangtze River South Channel waterway to Changxing Island and spanning Yangtze River North Channel waterway to east of Chongming Island.

Yangtze River begins to be divided into 3 levels of branches and have 4 mouths flowing into the sea: The

Figure 1. Site location of Chongming Crossing.

South Channel waterway is mixed river trench. The intermediate slow flow area forms Ruifeng shoal which is relatively stable for a long time. The natural water depth makes it as the main navigation channel. However, the North Channel waterway is located in the middle part of river, which is influenced by the south part and branch transition into North Channel waterway. So the trench varies alternatively and the river map is not as stable as South Channel waterway. Therefore, after iterative discussion by several parties, finally the solution of 'Southern Tunnel & Northern Bridge' is selected. The total project is 25.5 km long, among which 8.95 km is tunnel with a design speed of 80 km/h and 9.97 km is bridge and 6.58 km is land connection with a design speed of 100 km/h, as shown

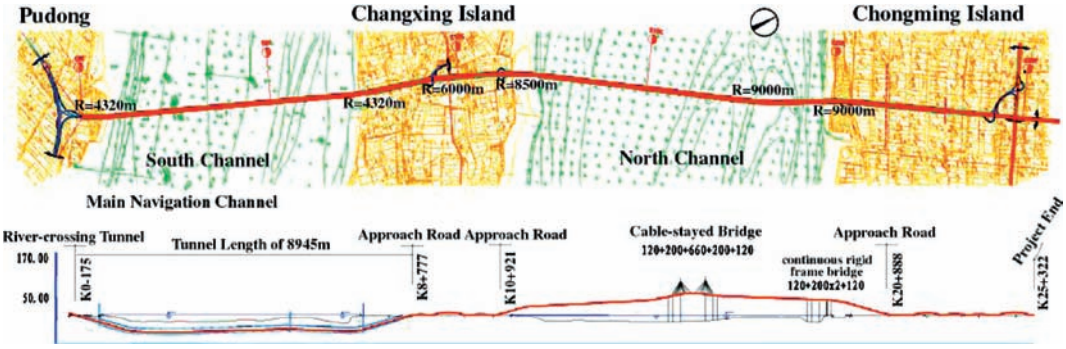

Figure 2. Diagram of Shanghai Yangtze River Tunnel and Bridge.

in Figure 2. The total roadway is planned as dual 6 lanes.

2 CONSTRUCTION BACKGROUND AND PLANNING

The planning study of Shanghai Yangtze River Tunnel and Bridge Project (Chongming Crossing) was incepted from 90s of last century. The preliminary preparatory work has lasted 11 years. In May 1993, the National Scientific Committee held the 'Yangtze River mouth crossing significant technical-economical challenges – early stage work meeting'. After one year special investigation, the 'Preliminary study report of significant technical challenges of 'Yangtze River Crossing' was prepared. The pre-feasibility study report was prepared in March 1999. In August 2001, the international concept competition was developed and the 'Southern Tunnel & Northern Bridge' solution was defined. The National Planning Committee approved the project proposal in December 2002. The feasibility study report was approved by the National Development and Reform Committee in November 2004. The preliminary design was approved by the Ministry of Communication in July 2005 and total investment of 12.616 billion RMB was approved for the project.

For the project construction investment, 5 billion was funded by Shanghai Chengtou Corporation (60%) and Shanghai Road Construction Cooperation (40%), and 7.6 billion was financed from Bank Consortium.

Based on the characteristics of the national major project, Commanding Post of Shanghai Tunnel & Bridge Construction was established with approval of Shanghai Municipal Committee. The post is directed by the vice major and composed of staff from Pudong New Area, Chongming County and other committees and bureaus. The main responsibility is to make decision on significant problems and coordinate important items. In order to improve the depth of daily management, office was set up under the commanding post, working together with established 'Shanghai Yangtze River Tunnel and Bridge Construction Development Co., Ltd.' which is mainly in charge of the implementation of the project and daily work of commanding post and performs the investment management on behalf of the client. The specific work is responsible for the financing, investment, construction, operation and transfer of the project. To detail the technical assurance measures, the clients sets up the technical consultant team which provides theoretical support, technical assistance and consultancy service for significant technical challenges during the implementation. Meanwhile, the team is involved in the investigation of significant technical solutions, review of construction method statement and treatment of technical problems to ensure the high quality and safety. International well-known consultancy companies are entrusted for the purpose of application of state-of-art philosophy, most successful experience, optimal concept and most mature management to make the Yangtze River Tunnel and Bridge Project as Century Elite Project.

The project finally initiated on 28th, December 2004 and planned to be open to traffic in July 2010. The main civil structure of the bridge is planned to be closed in June 2008, and tunnel in April 2009.

3 NATURAL CONDITIONS OF TUNNEL PROJECT

3.1 *Environmental conditions*

Shanghai Yangtze Tunnel Project starts from Wuhaogou of Waigaoqiao in Pudong New Area, connected with Shanghai main fast roads such as Middle Ring, Outer Ring and Suburb Ring through Wuzhou Aveneu, crossing southern water area and lands on Changxing Island 400 m west of Xinkaihe Harbour, connected with Changxing Island road net through Panyuan Interchange. The main building on land is the flood prevention wall on Pudong side and Changxing Island. Others are farm fields. The river-crossing section is mainly the

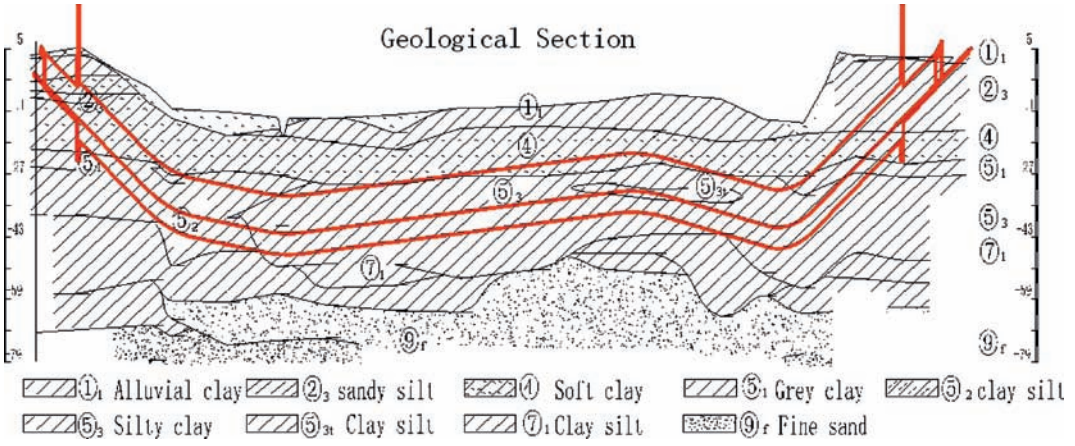

Figure 3. Longitudinal profile of tunnel.

southern water way for navigation which is an important passage for connecting Yangtze Waters with other seashore area in China and oceans worldwide.

There are two sea cables arranged along the bored tunnel axis with a depth of 3 m below natural river bed. One cable is basically located at the west side of the tunnel and goes into the river near Wuhaogou on Pudong side, which is about 1,500 m away from the tunnel. It becomes closer to the tunnel gradually to the north and crosses the tunnel to its east at 240 m from Changxing Island and lands on Changxing Island at 350 m west of Xinkaihe Harbour. The other cable goes into the river near Wuhaogou, 1,300 away from the tunnel. Then it turns to NE first and N at 2,600 m way from Pudong Land Connections, almost identical with the tunnel alignment. And it changes from the west of tunnel to east of tunnel gradually and lands on Changxing Island about 300 m west of Xinkaihe Harbor.

Furthermore, two sunken boats close to Chainage XK2+350 and XK1+500 have been salved before bored tunnel construction. Earth was also filled back at corresponding locations; however, there may be still some remains.

3.2 *River regime and hydrological conditions*

At the mouth of Yangtze River it is tide area with intermediate level. Outside of mouth is regular half day tide and inside is irregular half day shallow tide due to the change of tide wave. Average flood tide time is 5 h and average ebb tide time is 7 h, so total time for ebb and flux is 12 h. The average currency flow is 1.05 m/s for flood tide during flood season and 1.12 m/s for ebb tide. The maximal flow for flood tide is 1.98 m/s and 2.35 m/s for ebb tide.

The underground water type in the shallow stratum at tunnel site is potential water, which has close hydraulic relation with river water. The potential water level is mainly influenced by the Yangtze River flux and ebb. The average water level for Waigaoqiao and Changxing Island is 2.8 m and 2.4 m, respectively.

In the stratum ⑦ and ⑨ at site area, the confined water is rich. At most area, the confined water is directly continuous. The confined water level is between −4.15 m and −6.76 m. Furthermore, slight confined water distributes in $⑤_2$, which has certain hydraulic relations with confined water in ⑦.

3.3 *Geological conditions*

The relief of onshore area of the project is 'river mouth, sand mouth, sand island' which is within the major four relief units in Shanghai. The ground surface is even with a normal elevation of 3.5 m (Wusong Elevation). The water area is classified as river bed relief.

The project site has a seismic fortification intensity of 7, classified as IV site. The stratum $②_3$ and $③_2$ sandy silt distributing on Pudong land area is slightly liquefied.

Main geological layers (refers to Figure 3) TBM crosses are: $④_1$ grey muddy clay, $⑤_1$ grey muddy clay, $⑤_2$ grey clayey silt with thin silty clay, $⑤_3$ silty clay, $⑤_3$ tlens, $⑦_{1-1}$ grey clay silt, $⑦_{1-2}$ grey sandy silt, etc. Unfavorable geological conditions are experienced along the axis of the tunnel, such as liquefied soil, quick sand, piping, shallow gas (methane), lens and confined water, etc.

4 TUNNEL DESIGN SOLUTION

4.1 *Scale*

Shanghai Yangtze River Tunnel is designed as dual 6 lanes expressway, and rail traffic provision is made below the road deck. Seismic fortification level is 7.

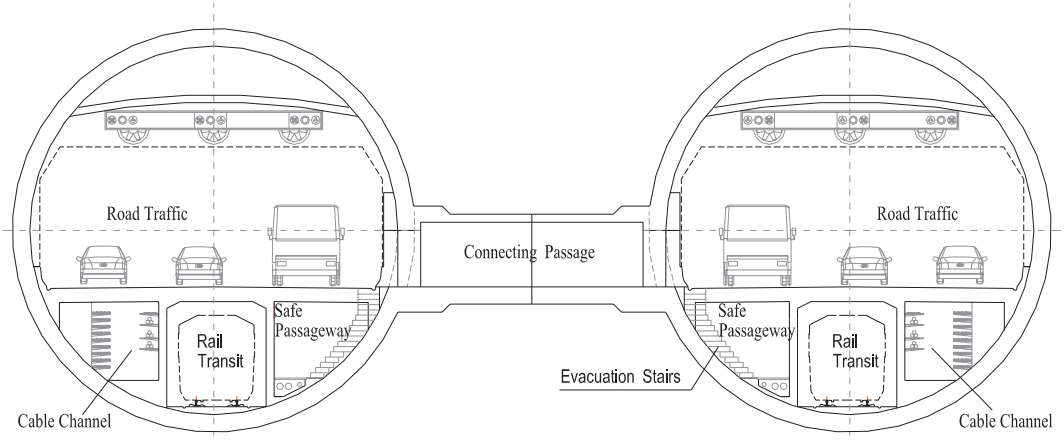

Figure 4. Cross section of bored tunnel.

Design service life is 100 years. The project consists of land connections of Pudong side (657.73 m), river-crossing tunnel (east tube 7,471.654 m and west tube 7,469.363 m) and land connections on Changxing Island (826.93 m). Total length is 8,955.26 m and investment is 6.3 billion RMB. The river-crossing part is twin-tube bored tunnel.

4.2 *Tunnel alignment*

The longitudinal profile of bored tunnel is in a shape of 'W' with a longitudinal slope of 0.3% and 0.87%. The land connections have a longitudinal profile of 2.9%. The minimal curvature radius of horizontal plane is 4,000 m and vertical profile 12,000 m.

4.3 *Building design*

4.3.1 *Cross section of bored tunnel*

Based on structural limit of traffic passage and equipment layout requirement, the internal diameter of lining for bored tunnel is determinated as 13.7 m considering the fitted tolerance of lining at curved section, construction tolerance, differential settlement, and combining the design and construction experience. On the top of tunnel, smoke discharge ducts are arranged for fire accident with an area of 12.4 m^2. Each tunnel has three lanes with a structural clear width of 12.75 m and road lane clear height of 5.2 m. The central part below road deck is for rail traffic provision in future. On the left side, beside the buried transformer arrangement, it also serves as main evacuation stairs. The right side is cable channel, including provision space for 220 kV power cable, as shown in Figure 4.

4.3.2 *Cross-section of land connections*

Working shaft is underground four-floor building: −1 is for ventilation pipe and pump plant for fire fighting; −2 is for road lane with cross over; −3 is for rail traffic provision and power cable gallery and −4 is for waste water pump plant.

The cut-and-cover is designed with a rectangular shape consisting of two tubes and one cable channel. 3 lanes are arranged in each tube. The structural limit is 13.25 m in width and 5.5 m in height, as shown in Figure 5. Upper area with a height of 0.6 m is for equipment provision. The upper part of central gallery is for cable channel, middle part for evacuation and lower part for pipe ditch. Ventilation shaft and building for equipments are arranged above the cut-and-cover tunnel close to the working shaft.

The approach consists of light transition zone and open ramp. The structural limit of cross section is identical with that of cut-and-cover tunnel. Both sides have a slope section with a slope of 1:3 with green planting for protection. The light transition zone is designed as steel arch structure.

4.4 *Structural design*

4.4.1 *Structural design of bored tunnel*

The external diameter of bored tunnel lining is 15,000 mm and internal diameter 13,700 mm, as shown in Figure 6. The ring width is 2,000 mm and thickness is 650 mm. Precast reinforced concrete common tapered segments are assembled with staggered joint. Concrete strength class is C60 and seepage resistance class is S12. The lining ring consists of 10 segments, i.e. 7 standard segments (B), 2 adjacent segments (L), and 1 key segment (F). According to the different depth, segments are classified as shallow segments, middle-deep segments, deep segments and extremely deep segments. Skew bolts are used to connect segments in longitudinal and circumferential direction. 38 × M30 longitudinal bolts are used to connect the rings. 2 × M39 circumferential bolts are used to connect the segments. Shear pins are added between

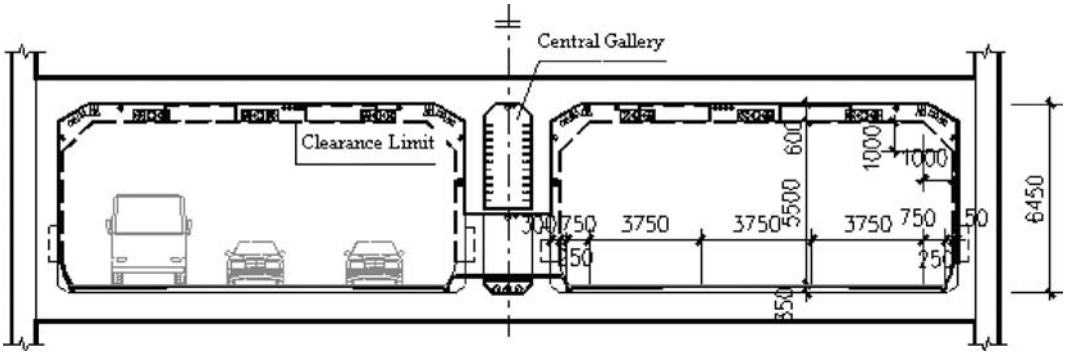

Figure 5. Cross-section of cut-and-cover.

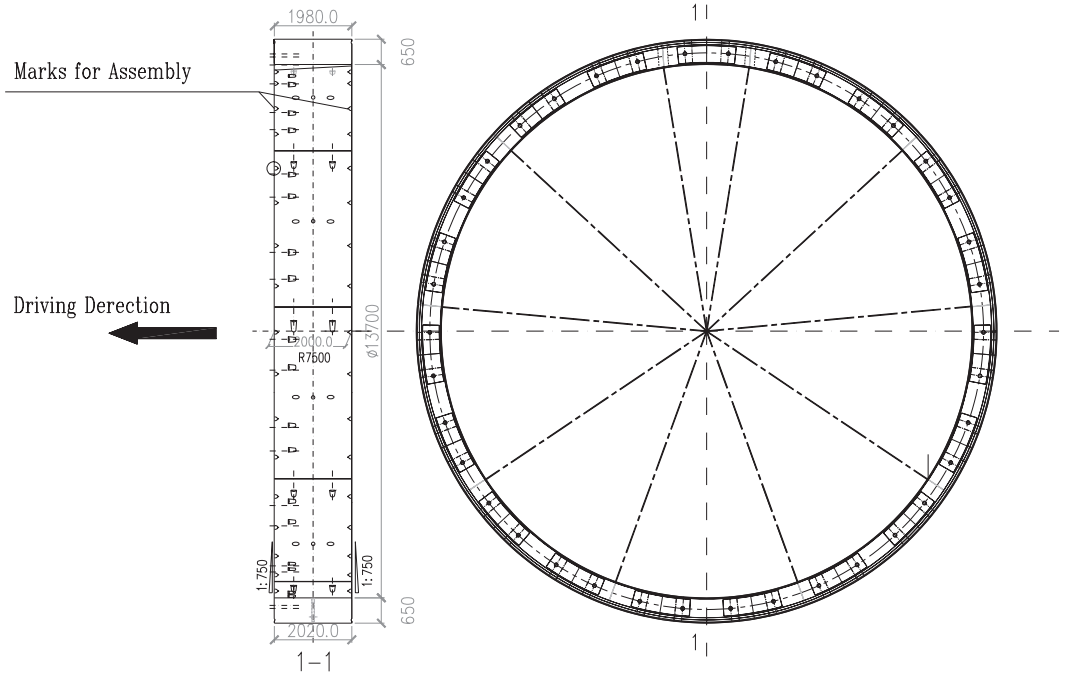

Figure 6. Lining structure.

lining rings at shallow cover area, geological condition variation area and cross passage to increase the shear strength between rings at special location and reduce the step between rings.

4.4.2 *Structural design of land connections*

The working shaft and cut & cover tunnel share the same wall. The thickness of diaphragm of working shaft is 1,000 mm, and the inner wall is 500 mm, 1,200 mm, respectively. For the cut-and-cover tunnel, the thickness of diaphragm is 1,000 mm, 800 mm, and 600 mm respectively depending on the excavation depth. The inner structure thickness is 600 mm.

For the open cut ramp, the bottom plate structure thickness is around 500–1,100 mm. Under the bottom plate, bored piles are arranged as up-lifting resistance pile to fulfil the structural floating resistance requirement. The slope uses in-situ cast reinforced concrete grid and fill earth and green planting in the grid for protection.

4.5 *Structural water-proof and durability design*

4.5.1 *Requirement and standard*

For the bored tunnel and working shaft, the water proof standard of slightly higher than level II is required. For

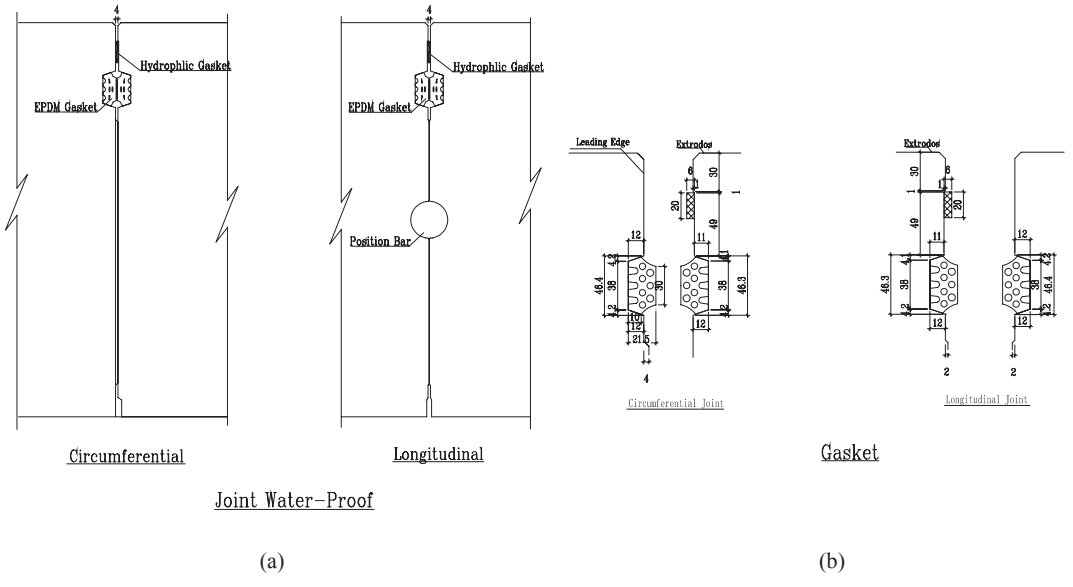

Figure 7. Segment joint water proofing sketch.

the entire tunnel, the average leakage should be less than 0.05 L/m^2·d. For each random 100 m^2, the leakage should be less than 0.1 L/ m^2·d. The inner surface wet spots should not be more than 4‰ of total inner specific surface area. In each random 100 m^2, the wet spots should not be more than 4 locations. The maximal area of individual wet spot should not be large than 0.15 m^2.

The chloride diffusion coefficient of concrete lining structure of bored tunnel is not more than 12×10^{-13} m^2/s. Concrete seepage resistance class is not less than S12. Furthermore, it is required that under 1 MPa water pressure which is equivalent to 2 times of water pressure for the tunnel with the largest depth, no leakage is occurred when the lining joint opens 7 mm and staggers 10 mm. The safety service life of water proof material is 100 years.

The seepage resistance class of onshore tunnel structure is not less than S10.

4.5.2 *Water proofing design*

The segment joint water proof arrangement consists of EPDM rubber strip with small compressive permanent deformation, small stress relaxation and good aging resistance performance and hydrophilic rubber strip, as shown in Figure 7.

The deformation joint at cut-and-cover tunnel uses embedded water stop gasket, outer paste gasket and inserted sealing glue forming enclosed system. The top plate uses water proof paint as outer water proof layer.

4.6 *Tunnel operation system*

4.6.1 *Ventilation system*

The road tunnel uses jet fan induced longitudinal ventilation combined with smoke ventilation.

The longitudinal ventilation area in tunnel is 82 m^2. Jet fans are suspended above the deck lane and below the smoke discharge duct, supporting induced ventilation in normal operation and congested condition. 78 jet fans with a diameter of 1,000 mm are arranged in each tube from Pudong access to Changxing Island access, every 3 as a group.

Ventilation shafts are arranged on Pudong side and Changxing Island, respectively, housing large ventilation machine and special smoke discharge axial fan. The fans are connected with main tunnel through air inlet and ventilation duct. During normal operation and congested condition, the ventilation machine is turned on to discharge the polluted air in the tunnel. 6 large axial fans with a capacity of 75 m^3/s – 150 m^3/s are housed in the working shaft on Changxing Insland and Pudong, respectively.

For normal operation of lower rail traffic, piston ventilation mode is used.

4.6.2 *Water supply and drainage system*

The fire water, washing waste water, and structural leakage are collected by the waste water sump at the lowest point of river. Sump is arranged at upper and lower level, respectively. The lower waste water is drained by the relay of upper sump. The upper sump is arranged on two sides of rail traffic area, housing

four pumps which are used alternatively under normal operation and turned on entirely during fire fighting. For lower level, 4 sumps with a dimension of 1,000 × 1,000 × 550 mm are arranged at the lowest point of tunnel where SGI segment is used and above the sump water collection trench with a length of 7 m and a width of 1 m is arranged. One waste water pump is placed in each pit which are used alternatively at normal condition and three are used, one spare during fire fighting.

At each access of tunnel, one rain water sump is arranged to stop water and drain it out of the tunnel. The rain amount is designed based on a return period of 30 years for rainstorm.

4.6.3 *Power supply system*

The electricity load in tunnel is classified as three levels: level I is for ventilation fan, valve, water pump, lighting and monitoring & control system and direct current screen, etc; level II is for tunnel inspection and repair, and ventilation fan in transformer plant; level III is for air conditioning cold water machines.

On Pudong side and Changxing Island, two transformers are arranged. Two independent 35 kV power circuits are introduced respectively and can be used as spare power for the other through two connection cables. Each route ensures the electricity load of level I and II in the tunnel. For the dynamical and lighting load far away from transformers, the power is supplied through 10 kV power supply network in the tunnel and embedded transformers underneath the tunnel to ensure the long distance power supply quality and reduce energy losses. 6 kV power is supplied for the concentrated ventilation fan. Lighting electricity is supplied by independent circuit in power supply system.

4.6.4 *Lighting system*

Light belt is used for lighting in the tunnel. At portal area, natural light transition and artificial light combination is used for lighting. Fluorescence lamp is the main light source in the tunnel. Strengthening lighting uses the high pressure sodium lamp. Taking account of the energy consumption, the application research of LED with high power is being developed. The shift time for emergency lighting in the tunnel should not be larger than 0.1 s and the emergency time is 90 min.

4.6.5 *Monitoring and control system*

The comprehensive monitoring system consists of traffic monitoring system, equipment monitoring system, CCTV monitoring system, communication system, fire automatic alarming system, central computer management system, monitoring and control center. Equipment monitoring system is classified as ventilation subsystem, water supply and drainage subsystem, lighting subsystem, and electrical monitoring subsystem. Monitoring system has access provision for health monitoring system, and expressway net traffic monitoring emergency center, rail traffic monitoring and 220 kV, etc.

The information collected by the tunnel monitoring system, bridge monitoring system, and toll station system is transferred to the monitoring and control center in the tunnel and bridge administration center on Changxing Island. Furthermore, one administration center is arranged at Wuhaogou on Pudong side assisting the daily management and emergency treatment, establishing the three level frame of 'monitoring and control center – administration center – outfield equipment'.

4.7 *Fire-fighting system*

The fire fighting sytem design cosists of balanced and redundant design of safety and function for the entire tunnel structure, building, water supply and drainage and fire fighting, emergency ventilation and smoke discharge, lighting, power supply and other subsystems. The details are as follows:

- Cross passage is arranged every 830 m connecting the upchainage and downchainage tunnel for passenger evacuation with a height of 2.1 m and width of 1.8 m. Three evacuation ladders are arranged between two cross passages connecting the upper and lower level.
- The passive fire proof design uses the German RABT fire accident temperature rising curve. The fire accident temperature is 1,200°C. Fire proof inner lining which ensures the surface temperature of protected concrete segment is not more than 250°C within 120 minutes is selected to protect the arch above smoke duct, smoke duct and crown above the finishing plate. For rectangular tunnel, fire proof material which ensures the structure top plate safety within 90 minutes is selected to protect the top plate and 1.0 m below the top plate. To ensure the passenger evacuation, fire proof bursting resistance fibre is mixed in the concrete bulkhead to achieve no damage of structure when structure is exposed to fire for 30 minutes.
- The ventilation system is designed based on only one fire accident in road tunnel and rail traffic area. The marginal arch area of bored tunnel is used for smoke duct. Special smoke ventilation valve is arranged every 60 m for the smoke ventilation in case of fire accidents on road level. When fire accident occurs in lower level, ventilation fan in the working shaft is turned on to ventilate the smoke to the side of fire source while passengers evacuate towards the fresh air.
- The emergency lighting is arranged on two sides with the same type. As the basic lighting, inserted into the basic lighting uniformly. Meanwhile, normal lighting and emergency lighting are installed in

the cable passage. Evacuation guidance signs are arranged on the two sides of road, cross passage and safety passage. Emergency telephone guidance signs are arranged above the telephones in tunnel.

– Fire water supply at both ends of tunnel is from the DN250 water supply pipe introduced from two different municipal water pipes without fire water pond. One fire fighting pump plant is arranged in working shaft on Pudong side and Changxing Island, respectively. The fire hydrant system is continuous in the longitudinal evacuation passage. Fire hydrant group is arranged every 50 m at one lane side in each tunnel and fire extinguisher group every 25 m. Foam-water spraying system is used in the tunnel which can provided foam liquid continuously for 20 min and arranged every 25 m.
– The communication and linkage of each subsystem of comprehensive monitoring and control system can realize the monitoring, control and test of the whole tunnel such as fan, water pump, electrical and lighting equipment. Fire automatic alarming system can detect the possible hazards such as fire fast, real-time identify and alarm and has the function of passage alarming and tunnel closed. Furthermore, corresponding equipments can be automatically activated to extinguish the fire at early time and organize the hazard prevention to reduce the loss to the minimum extent.

5 Φ15, 430 MM SLURRY MIXED TBM

Two large slurry pressurized mixed shield machines with a diameter of 15.43 m are used for the construction of 7.5 m long bored tunnels.

5.1 *TBM performance and characteristics*

The TBM consists of shield machine and backup system with a total length of 13.4 m and weight of 3,250 t, including cutter head system, shield body, tailskin, main drive, erector, synchronized grouting system, transport system, guidance system and data acquisition system and slurry system.

The TBM has excavation chamber and working chamber. During advancing, the air bubble in the working chamber is adjusted through the control unit to stabilize the slurry level thus balance the water/soil pressure in excavation chamber, as shown in Figure 8.

The thrust system consists of 19 groups thrust cylinders with a total thrust force of 203,066 kN. Cutter head is drived by 15 motors with 250 kW power, so the total power is 3,750 kW. Installation position for two spare motors is also provided. Tailskin seal structure is composed of three rows steel wire brushes and one steel plate brush, forming 3 grease chambers. The erector system is centrally supported with 6 freedom

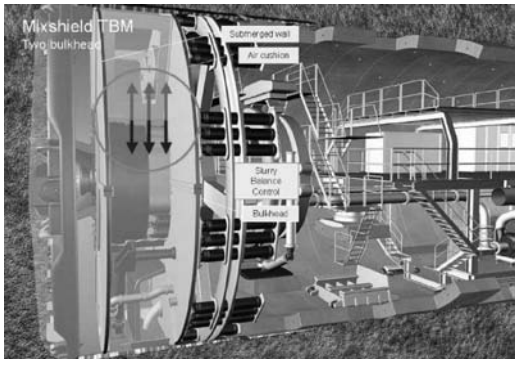

Figure 8. Bulkhead of Mixshield TBM.

degrees. Vacuum suction plated is used to grasp the segment. 6-point grouting is used for simultaneous grouting.

Backup system consists of 3 gantries: gantry 1 housing the power equipment and control system, gantry 2 housing 3 cranes and bridge section for segment, road element, and other construction material transport, gantry 3 is pipe laying gantry for carrying the extension of the different services such as cable hose, slurry, air and industrial water pipes.

Excavated soil is transported from excavation chamber to the slurry treatment plant (STP) through the slurry pipe in the slurry circulation system. After separation by the treatment equipment, excavated soil with large size is separated and then the recycled slurry is pumped back into excavation chamber and working chamber.

5.2 *Adaptability to the 'large, long and deep' characteristics*

For the TBM construction, firstly the project and crew safety should be ensured. The key for safety of TBM is to protect the cutter head and tailskin, mainly including cutter head design, main bearing seal and tailskin seal assurance. Furthermore, the maintenance and repair of these parts are risk and difficult to access, so the inspection and possibility for maintenance in case of failure must be considered.

5.2.1 *Cutter head and cutting tools*

Cutter head is for soft ground and can be rotated in two directions. The cutter head is pressure resistant steel structure and specific wear protection is arranged for the periphery area. Special wear protection is also designed for cutting tools.

The closed type cutter head is designed with 6 main arms and 6 auxiliary arms, 12 large material opening and 12 small material opening. The opening ratio is around 29%. 209 cutting tools are arranged on

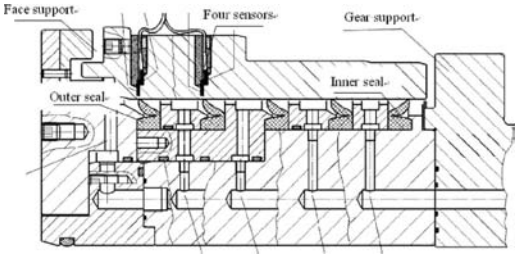

Figure 9. Main bearing seal arrangement.

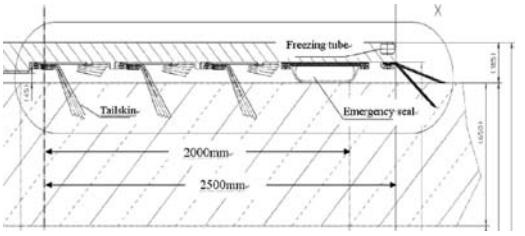

Figure 10. Tailskin structure.

the cutter head, among which 124 fixed scrapers, 12 buckets, 2 copy cutters, 7 replaceable center tools and 64 replaceable tools.

The scrapers are custommade large tools with features of 250 mm width, wear-resistance body and high quality carbide alloy cutting edges whose angle matches the parameter of excavated ground. The scrapers at the edge are used to remove the excavated soil at edge and protect the cutter head edge from direct wear. Copy cutter can automatically extend and retract. The multiple over-cut areas can be setup in the control cabin and corresponding cutting tools position are displayed. The replaceable cutting tools have special seal to prevent the slurry at the front surface enter into the cutter head chamber. During operation, the workers can enter the cutter head chamber to replace the cutting tools under atmospheric condition with high safety, good operation possibility and low risk.

In order to avoid clogging at cutter head center, the opening at center is designed as chute to ease the material flowing. Meanwhile, one bentonite hole is arranged at each opening to ease flushing in case of clogging.

5.2.2 *Main bearing seal*

Two sets seal system are arranged for the main bearing seal design. The outer seal is for the excavation chamber side and inner seal for the shield body with normal pressure. The special seal combination can bear a pressure of 8.5 bar.

Outer seal is to separate the main bearing and excavation chamber. Seal type is axial seal with large diameter, totally 4 lip seals and one pilot labyrinth, thus forming 4 separate areas, as shown in Figure 9.

The inner seal one the gear box side is special axial seal which can carry the pressure of gear chamber.

The seal system has grease lubrication and leakage monitoring system which can monitor the grease amount by pressure and flow monitoring. The seal system has been proved successfully in many projects for several years and become a standard configuration.

5.2.3 *Tailskin*

The tailskin is sealed off by 3 rows steel wire brush and 1 steel plate brush, as shown in Figure 10. Furthermore, 1 emergency seal is arranged between the 3rd row steel wire brush and the steel plate brush. The emergency seal has the function to protect the ring building area from water ingress while changing the first three steel brush seals. Due to no practical application references of this technology, modeling test has been carried out for the emergency seal installation to confirm the reliability of the emergency seal when the inflatable seal is pressurized to 1 MPa.

Simultaneous grouting lines are arranged at the tail skin, including one standard grout pipeline and one spare pipeline for filling the annulus gap outside the segment after excavation. Furthermore, 19 chemical grout pipes are added for special hardening grout (simultaneous slurry penetrating into cement) or polyurethane for leakage block in emergency condition. 19×3 grease pipes have the function of steel wire brush lubrication and tail skin sealing. The seal system is controlled from the cabinet in automatic and manual modes through time and pressure control.

Furthermore, freezing pipelines are arranged at the tailskin to ease the ground treatment by means of freezing measures in case of leakage and ensure the seal treatment and repair safety.

5.2.4 *Man lock and submerged wall*

During long distance advancing, there is a possibility of operation failure of mixing machine due to large obstacles blocking such as stones, main bearing seal replacement due to wear, submerged wall closed or leakage examination in the air bubble chamber. These maintenance and repair work need workers access the air bubble chamber with a pressure up to 5.5 bar. Therefore, two man locks are arranged to ensure the maintenance and repair workers can access.

The main chamber of manlock can house one 1.8 m stretcher. Under pressure-reducing condition, the medical staff can access the main chamber and organize rescue in case of emergency. Meanwhile, the other man lock can transport the tools, material and equipment from TBM to the air bubble chamber.

The man lock is equipped with poisonous gas detection system which can take the sample of enclosed gas in the man lock. The system information will be displayed at the working position where outside

staff is. The man lock also provides the flange connection. Once the rescue and injuries enters into temporary rescue chamber, the temporary chamber can be disassembled fast and transported out of the tunnel, connected with large medical chamber for the convenience of medical work to rescue.

The submerged wall uses hydraulic drive and is equipped with air pressure seal strip. When normal operation in the working chamber is needed, the submerged wall can be closed thus the excavation chamber and working chamber can be separated, and then the valve can be opened for reducing the pressure. At this time, pipe for supplementing slurry which penetrates working chamber can maintain the slurry pressure in the excavation chamber.

6 TUNNEL CONSTRUCTION METHOD

6.1 *Overall arrangement and time schedule*

Based on the overall programming, the construction of working shafts, bored tunnel, synchronous construction of road structure, operation equipment installation and commissioning are the main works and secondary works such as receiving shaft and crosspassage in parallel.

In May 2006, the launching shaft and onshore structures on Pudong side were completed and site assembly of two TBMs started. The east tunnel starts advancing in September 2006, while west tunnel in January 2007. During construction of these two tunnels, the prefabricated road element erection and TBM advancing are synchronous, which on one hand resist the tunnel floating during construction stage and on the other hand provide special truck passage for segments, prefabricated road elements and materials to realize the fast bored tunnel construction. In parallel with bored tunnel construction, the road deck structure construction is also carried out 200–250 m back from segment erection and top smoke duct will start construction in January, 2008, forming gradually working flow in tunnel. After west tube TBM advancing 3 km, the first crosspassage started construction in October, 2007. After the tunnel is through, final connection work of working shaft and road structure is carried out and operation equipment and finishing and pavement work will start.

6.2 *Main critical technical issues during bored tunnel construction*

6.2.1 *TBM launching and arriving technology*

6.2.1.1 TBM launching

(1) Tunnel eye stabilization

3-axial mixing pile and RJP injection procedure is used surrounding the working shaft to stabilize the ground forming a stabilized area of 15 m in length. 6 dewatering wells for bearing water are supplemented beyond the treated ground area and holes are bored for grouting the annulus to ensure the safety during tunnel gate removal. These three measures application has achieved good performance. During TBM launching, the treated soil is stable.

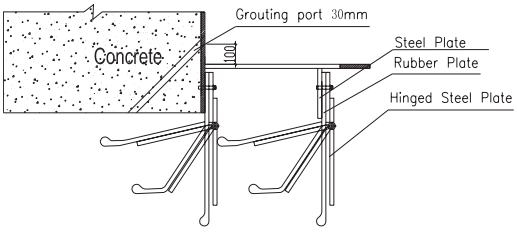

Figure 11. Water stop tank sketch.

(2) Tunnel annulus seal

The diameter of tunnel eye is up to 15,800 mm. To prevent the slurry enters into the working shaft from the circular build gap between tunnel eye and shield or segment during launching thus affect the establishment of front face soil and water pressure, good performance seal water stopping facility is arranged. The facility is a box structure with 2 layers water stop rubber strip and chain plate installed, as shown in Figure 11. The outside chain plate is adjustable with 50 mm adjustment allowance. Furthermore, 12 grout holes are arranged uniformly along the outside between two layer water stop on the box for the purpose of sealing in case of leakage at the tunnel eye. The outer end surface of water stop facility shall be vertical to the tunnel axis.

(3) Back support for TBM

The back up shield support includes 7 rings, among which -6 is steel ring composed of 4 large steel segments with high fabrication quality to ensure the circularity and stiffness of the reference ring, as shown in Figure 12. After precise positioning of steel ring, it is supported on the concrete structure of cut and cover tunnel by 19 steel struts with a length of 1.2 m. Other 6 minus closed rings segments are assembled with staggered joint. Inserts are embedded on the inside and outside surface. After each ring building, the circumferential ring and longitudinal ring are connected with steel plate to improve the integrate stiffness and ensure the circularity and ring plane evenness. Meanwhile, the circumferential plane of each minus ring shall be vertical to the design axis.

6.2.1.2 TBM receiving

(1) Arrangement in receiving shaft

Before TBM receiving, the diaphragm between receiving shaft and cut & cover tunnel and the diaphragm in the receiving shaft between upchainage and downchainage tunnel shall be completed to make the receiving shaft as an enclosed shaft structure. Then MU5 cement mortar is cast in the working shaft with a height

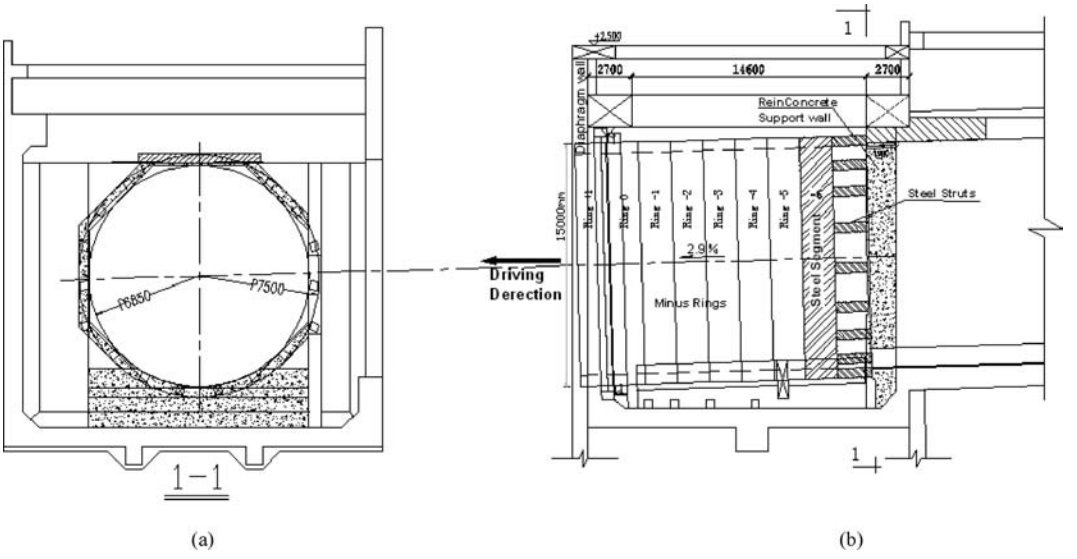

Figure 12. Back supports for TBM.

of 3 m higher than the TBM bottom. Steel circumferential plate is arranged along the steel tunnel annulus. The inner diameter of steel plate is 5 cm larger then TBM. 18 grout holes are arranged surrounding the tunnel annulus and inflatable bag is installed in the tunnel eye.

(2) TBM arriving

When the cutting surface of TBM is close to the concrete wall of tunnel eye, advancing is stopped. Then pump water in the receiving shaft to the underground water level. Meanwhile, inject double grout into the annulus 30 m back from tailskin through the preset grout hole on the segment to stabilize the asbuilt tunnel and block the water/soil seepage passage between untreated ground and TBM.

After above work, the TBM starts excavation of C30 glass fibre reinforced concrete and accesses the working shaft. The cutting surface accesses into the working shaft and the cutter head will cut the MU5 cement mortar directly and sit on the mortar layer. During accessing into the working shaft, polyurethane is injected through the chemical grouting holes.

(3) Tunnel eye sealing and water pumping

When 2/3 of TBM accesses the receiving shaft, water pumping is started. After pumping the water in the working shaft, continue the TBM advancing and inject the grout timely. When the TBM is in the working shaft, fill air in the inflatable bag in time to make the inflated bag seal the circumferential gap. Meanwhile, grouting is performed through the 18 holes on the tunnel annulus. Grout material is polyurethane. After the gap is fully filled with the grout, the air in inflated bag could be released slowly under close observation. If any water leakage is observed, the polyurethane shall be injected again for sealing.

When the tunnel gate ring is out of the tailskin, the welding work between ring steel plate, seal steel plate and embedded steel plates shall be done immediately to fill the gap between tunnel gate ring and tunnel.

6.2.2 *TBM advancing management*

6.2.2.1 Main construction parameters

During TBM construction, the construction parameters shall be defined and adjusted based on theoretical calculation and actual construction conditions and monitored data to realize dynamical parameter control management.

The advancing speed at beginning and before stop shall not be too fast. The advancing speed shall be increased gradually to prevent too large starting speed. During each ring advancing, the advancing speed shall be as stable as possible to ensure the stability of cutting surface water pressure and smoothness of slurry supply and discharge pipe. The advancing speed must be dynamically matching with the annulus grout to fill the build gap timely. Under normal boring condition, the advancing speed is set as 2–4 cm/min. If obstacles varying geological conditions are experienced at the front face, the advancing speed shall be reduced approximately according to actual conditions.

Based on the theoretical excavation amount calculated from formula and compared to actual excavated amount which is calculated according to the soil density, slurry discharge flow, slurry discharge density, slurry supply density and flow, and excavation time, if the excavation amount is observed too large, the slurry

density, viscosity and cutting face water pressure shall be checked to ensure the front surface stability.

In order to control the excavated soil amount, the flow meter and density meter on the slurry circuit shall be checked periodically. The slurry control parameters are: density $\rho = 1.15–1.2$ g/cm^3, viscosity = 18–25 s, bleeding ratio <5%.

Single type grout is used to inject at 6 locations, which is controlled by both pressure and grout amount. The grout pressure is defined as 0.45–0.6 Mpa. Actual grout amount is around 110% of theoretical build gap. 20 h-shear strength of grout shall not be less than 800 Pa and 28 day strength shall be above the original soil strength.

6.2.2.2 Shallow cover construction

At the launching section, the minimum cover depth is 6.898 m, i.e. 0.447 D, which is extremely shallow. To ensure the smooth advancing, 1–2 m soil is placed above the top. Meanwhile, in order to prevent slurry blow-out, leakage-blocking agent is mixed in the slurry and surface condition is closely monitored.

6.2.2.3 Crossing the bank of Yangtze River

Before the TBM crossing, the terrain and land feature in the construction surrounding area are collected, measured and photographed for filing. 155 monitoring points are arranged along the bank in 7 monitoring sections. During TBM crossing, the pressure is set according to the water pressure at excavation surface calculated for each ring. The slurry parameter is also adjusted timely based on the surface monitoring information. Grease injection at tail skin is performed well to avoid leakage and synchronous grout amount and quality are strictly controlled.

6.2.2.4 Adverse geological condition

(1) Shallow gas

When the TBM is crossing the deposit on Pudong side, methane gas may be experienced in the shallow area. At this time, the ventilation in the tunnel shall be increased to ensure good ventilation conditions of TBM. The concentration test of methane and combustible gas are carried out.

(2) Lens

Prior to the construction, geological investigation is carried out to learn the general location of prism. During construction, the TBM is set with suitable speed to cross the stratum as fast as safely possible.

(3) Bored hole

Due to the tunnel alignment adjustment, 9 geological bored holes will be experienced along the TBM advancing. During crossing, slurry with large density is used and polyurethane is injected surrounding the tunnel after crossing.

6.2.3 *Quality assurance technical measures for large tunnel*

6.2.3.1 Segment prefabrication

Nine sets steel formwork with high preciseness are used for segment prefabrication to fulfill the technical requirement to segment such as allowable width tolerance ±0.40 mm, thickness tolerance +3/−1 mm, arc length ±1.0 mm, circular surface and end surface plainness ±0.5 mm. In order to control prefabrication preciseness strictly and ensure the production quality, special laser survey system is introduced to conduct accurate measurement of segment profile dimension beside traditional survey measurement tools and segment trial assembly.

Fly ash and slag are mixed in the concrete for segment prefabrication. Strictly concrete casting, vibrating and curing procedures are used to control cracks and achieve the water proofing and durability requirement.

6.2.3.2 Segment assembly

The segment assembly shall satisfy the fitted tunnel design axis requirement by segment selection (rotation angle) and meanwhile make the longitudinal joint not on the same line. During the whole assembly process, for straight line, the principle is to erect on left and right at intervals. For curved section, the suitable segment rotation angle shall be selected based on TBM attitude, and segment lipping data.

Secondly, the relative dimension between segment and shield shall be checked to correct the positioning of each ring segment.

Then, each segment building shall be closely contacted. The ring plane and 'T' joint shall be even.

Finally, strictly control the lipping of ring. When the segment lipping exceeds the control value, the rotational angle of segment shall be adjusted timely to ensure the verticality between segment and tunnel axis.

6.2.3.3 Floating-resistance of tunnel

Due to the tunnel diameter up to 15 m, the floating resistance and deformation control during construction for large diameter tunnel are very challenging. The technical measure is mainly to improve the synchronous grouting management. Mortar type grouting material with cementation property is injected at multi-points. Furthermore, grout package with certain strength shall be formed surrounding the tunnel timely to resist the tunnel upfloating. Meanwhile, the tunnel axis shall be strictly controlled during construction and the tight connect between segments shall be improved to achieve the tunnel-floating resistance.

6.2.3.4 Ground deformation control

The ground settlement during TBM construction is mainly contributed by the front surface slurry pressure setup, annulus grouting and shield body tamper.

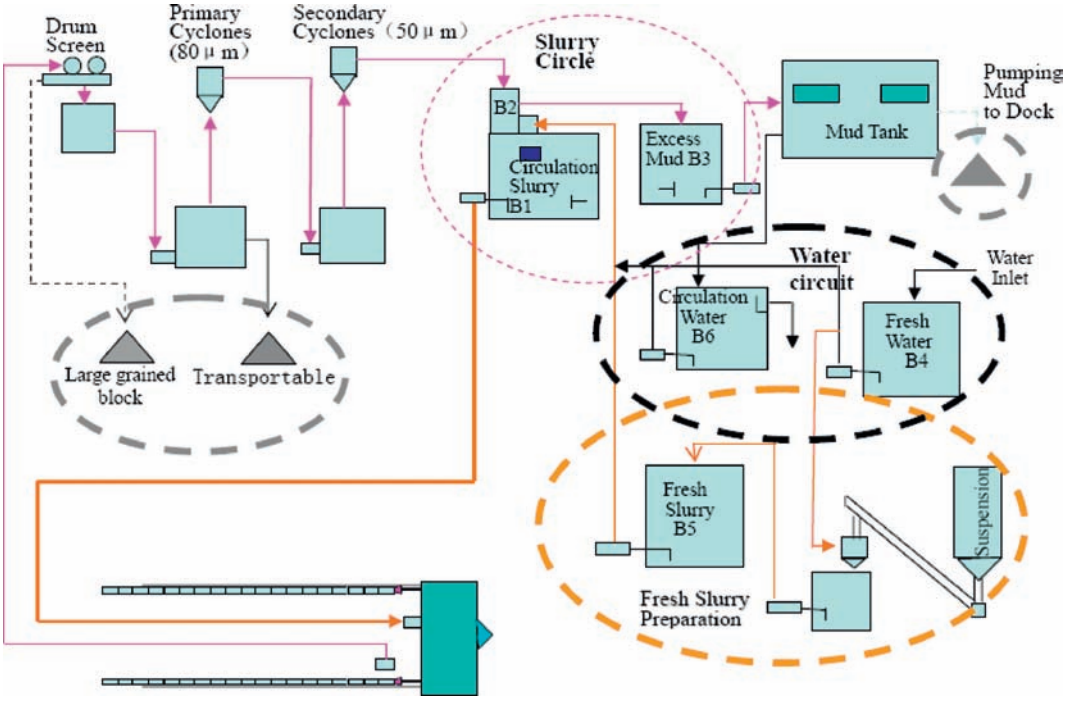

Figure 13. STP system flow chart.

Therefore, the ground settlement variation can directly reflect the TBM construction parameters setup. The crew can correct the construction parameter based on settlement monitoring to increase the deformation.

6.2.4 *Back-up technology for long distance TBM construction*

6.2.4.1 Slurry treatment and transport

The slurry separation system consists of subsystems of treatment, conditioning, new slurry generation, slurry discharge and water supply; with a capacity of 3,000 m^3/h to fulfill the advancing requirement of 45 mm/min, as shown in Figure 13. Based on the geological conditions along the tunnel alignment, the treatment system selects 2 level treatment methods. The initial treatment uses two rolling shieve to separate soil with a size of larger than 7 mm. For secondary treatment, firstly grain with a size of large than 75 is separated by $4 \times \phi 750$ mm cyclones and then grain with a size of large than 40 μm is separated by $12 \times \phi 300$ mm cyclones. The slurry spilled at the top of cyclone is transported to conditioning tank for reuse. After adjustment, the density of supplied slurry is 1.05–1.35 g/cm^3. The maintained optimal value is between 1.20 and 1.30 and d50 is between 40 and 50 μm. The STP system circulation efficiency is up to 70%. Discharged slurry and waste is transported to the bardge at riverside by pipes and trucks. The slurry supply pipe has a diameter of 600 mm and discharge pipe 500 mm. To ensure the long distance slurry supply velocity of 2.5 m/s and discharge velocity of 4.2 m/s to avoid slurry settlement in pipe and maintain not too high pressure in the pipe, one relay pump is arranged every 1 km. The pressure at pump outlet is controlled within 10 bar.

6.2.4.2 Axis control and construction survey guidance

Static measurement with GPS control net is used for surface control survey. For elevation control, GPS elevation fit method is used for elevation transfer. Part of basic traverse mark every 500 m is selected as main traverse. In the tunnel, level II subtraverse is used for the plane control, i.e. construction traverse and control parallel traverse. The control mark has a spacing of 600–900 m. The elevation control survey in tunnel uses level II. The fixed level mark is arranged with a spacing of 80 m.

6.2.4.3 Construction ventilation and fire protection

Due to the large diameter, long distance and 'W' longitudinal slope, especially when the TBM is advancing with a upgrading slope, the heat and humidity generated at the working face can not be discharged naturally thus concentrate at the working face in a shape of fog. Meanwhile, heavy trucks for construction material transport also cause a large amount of waste air

in the tunnel. Bad environment will have unfavorable influence on TBM equipment and crew, and also affect the smooth progressing of survey activity.

During construction stage, 2 special axial fans (SDF-No18) are arranged on the surface to provide fresh air to the space below road deck in the tunnel, then the relay fan and ventilation system equipped on the gantry will transport the fresh air to working surface. Meanwhile, other ventilation equipment on the gantry provides fresh air to main secondary equipments of TBM such as transformer, hydraulic equipment and electrical installations.

Adequate fire extinguishers are arranged in the shield and gantry and also oxygen, poisonous gas protection mask are equipped. Fire extinguisher is equipped on each transport truck. Safety staff is equipped with portable gas analysis device for check the air quality in tunnel every day.

6.2.4.4 Material transport

Segment, grout and prefabricated elements, etc are transported to the working area by special trucks from ramp area, through cut & cover tunnel and road deck which is constructed synchronously. Truck transport can avoid the derailing problems during traditional electrical truck transport. Furthermore, the truck has two locos, so the transport efficiency is high.

Prefabricated road element is transported to the gantry 2 by trucks and then lifted and erected by the crane on the bridge beam. Segments are transported to gantry 2 and then transferred to the segment feeder by the crane on the bridge beam and then transported to erection area.

6.2.5 *Critical equipment examination and replacement technology*

6.2.5.1 Main bearing sealing

Four supersonic sensors are installed in the seal arrangement for monitoring the main seal wear condition. Once the abrasion reaches certain value or grease leakage is monitored in the tank, it indicates the main seal needs to be rotated to another oritentation.

Once the seal wear is observed beyond preset value, the surface could be moved to ensure the replacement of main bearing seal. During replacing, the slurry in the chamber must be drained and provide effective support to excavation face. The operation staff shall go to the slurry camber to replace the seal under certain pressure.

6.2.5.2 Abrasion measurement and replacement of cutting tools

The system will be installed on 8 selected scraper positions as well as on two bucket positions. It will be connected to a plug at the rear of the cutting wheel to allow for simple condition diagnosis from a readout device. Conductor loop is embedded in the device. The wear condition of cutting tools can be indicated by checking the closed/open status of loops.

The worker accesses the cutting wheel arms from the center of the main drive. The worker installs the lowering/ lifting frame (with bolts) and screws it to the fixing plate of the tool. The fixing plate is then unscrewed. The worker will then lower the tool using the frame (with bolts). The pressure-tight gate will be closed down. The worn out tool shall be then exchanged with a new one. The tool will be lifted to position behind the gate. The gate will be opened. Then the tool will be put in its final position. The fixing plate is then screwed to the tool support. The frame is transferred to the next tool.

6.2.5.3 Tail seal and steel wire brush replacement

When the leakage is experienced at tail skin, and steel brush is defined to be replaced necessarily, open the emergency sealing and erect special segments. Strengthen the surrounding soil at tail skin with freezing method and then replace first 2 or 3 rows steel brush.

6.3 *Synchronous construction of road deck*

The synchronous construction of road structure includes erection of road element, segment roughening and drilling for inserting rebar, prefabrication of two side ballast, insitu cast corbel and road deck on two sides. According the variation and trend of asbuilt ring deformation and settlement, and the construction progress of 12 m (6 rings) per day and based on the requirement of deformation joint arrangement every 30 m, the construction is organized and arranged as flowing operation every 15 m. As shown in Figure 14, the basic construction procedure is as follows:

- Road element installation, 25 rings later than segment erection.
- Segment roughening includes the junction surface between ballast and segment and segment inner surface at corbel. The insert bar placing includes the Φ16 bar at ballast and Φ20 bar at corbel. The roughening works at ballast position is carried out at gantry 2, and the roughening operation platform at corbel is fixed to gantry 2. Insert bar placing is following gantry 3. The roughing machine is equipped with dust suction facility which can eliminate the dust to maximum extent.
- Reinforcement placing, formwork erection and concrete casting for ballast is carried out at 15 m behind the gantry 3 and 15 m more behind for corbel, and then another 15 m for road deck. Road deck concrete casting works are located at 250 m–300 m from the segment erection area. After casting, the curing with frame lasts 3 days and formwork is removed on the 4th day. After 28 days curing, the road deck can be open to traffic. During curing, the

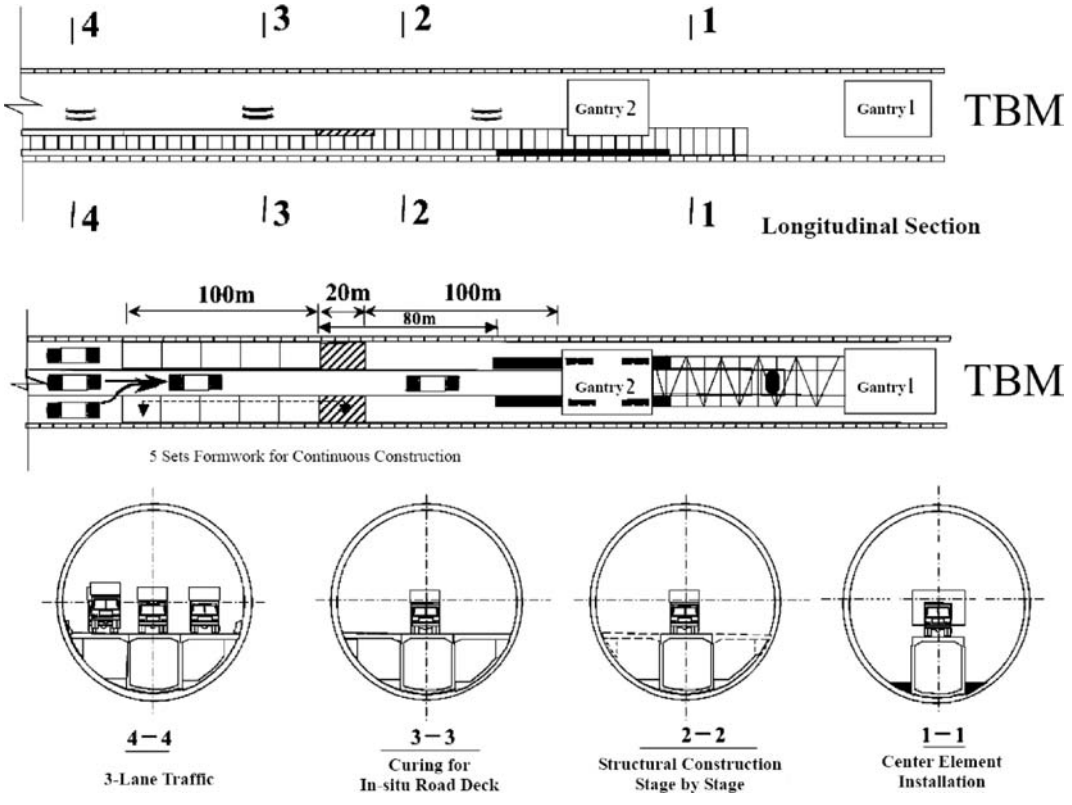

Figure 14. Synchronous construction flow chart.

road deck area is separated. Concrete mixing truck is used for concrete casting.

6.4 *Cross passage construction*

The cross passage which connects the two main tunnels has a length of around 15 m and diameter of 5 m. The construction will be by freezing method for soil strengthening and mining method for excavation.

The freezing holes are arranged as inside and outside rows which are drilled from two sides. The freezing is done from one side or both sides. Inside row holes are drilled from upchainage tunnel, 22 in total and outside row holes are drilled from downchainge tunnel, 18 in total.

Mining method will be used for excavation by area division. Firstly, pilot with a horn opening is excavated, and then the cross passage is excavated to design dimension. The fullsection excavation is done with a step of 0.6 m or 0.8 m.

When the main structure concrete strength reaches 75%, enforced thawing will be carried out. The hot brine for thawing circulates in the freezing pipe and the frozen soil is thawed by section. Based on the informational monitoring system, the soil temperature and settlement variation is monitored. Grouting pipe is arranged at shallow and deeper area for dense grouting. The overall principle for thawing is to thaw the bottom part, then middle part, and lastly the top part, as shown in Figure 15. When thawing by section is done in sequence, one section is being thawed and subsequent sections maintain the freezing for the purpose of maintaining the cross passage structure and main tunnel as an integrated part thus settlement avoidance before the section grouted.

6.5 *Land connections construction*

The profile dimension of working shaft is 22.4 × 49 m, with a depth of 25 m. 1.0 m thick diaphragm with a depth of 45 m is used for retaining structure. Open cut is used for excavation. The support system consists of 5 layers reinforced concrete and 1 layer steel support. Inside the pit, 3 m below the bottom, injection is done interval to make the strength not lower than 1.2 MPa. 13.5–16.0 m outside the working shaft is treated. For

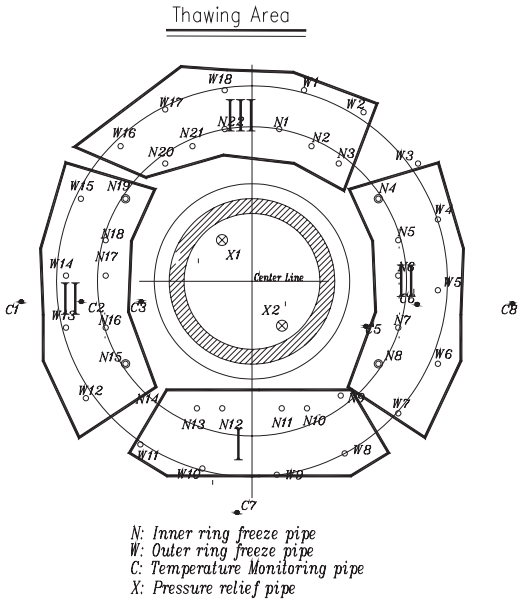

Figure 15. Divided thawing area of cross passage.

diaphragm at the TBM accessing into the receiving shaft, GFPR is used instead of normal reinforcement so that the TBM can cut the retaining wall directly and thus avoid the reinforcement cutting and tunnel eye concrete removal, which simplifies the construction procedure, accelerates construction progress and reduces the construction risk.

The excavation depth of pit for Pudong cut-and-cover is 23.1–9.9 m, and Changxing cut-and-cover 17.2 m–8.4 m. According to the excavation depth, diaphragm with thickness of 1.0 m, 0.8 m and 0.6 m is selected respectively. The support system is composed of reinforced concrete support and steel support. 3 m underneath the pit bottom is strengthened by rotating injection and also the junction between working shaft and cut-and-cut outside the pit to ensure the pit excavation stability.

The ramp is open cut with a slope of 1:3. The slope is protected through green planting in the reinforced concrete grid which is anchored in soil by anchors to prevent from sliding. In order to avoid slope sliding, the slope is strengthened by cement mixed piles with a diameter of 700 mm.

7 CONCLUSION

During the process from planning to implementation, Shanghai Yangtze River Tunnel has experienced various challenges. Technical support of tunnel construction from China and abroad is provided. With indenpendently developed and owned IPR and featured TBM tunnel construction theory and core technology is established, forming the core technology of large and long river-crossing TBM tunnel in China. Special technical issues such as lining structure design of extremely large tunnel, long distance TBM construction and hazard prevention system for long and large tunnel achieve to be internally state-of-art. Relevant standards, codes, guidance, specification and patent technology are developed to improve the technical system of tunnel construction in China and upgrade the internal competence of tunnel engineering.

REFERENCES

Cao, W.X. et al. 2006. Shanghai Yangtze River Tunnel Project design. *Shanghai Construction Science and Technology* 5: 2–6.

Chen, X.K. & Huang, Z.H. 2007. Shanghai Yangtze River Tunnel TBM cutting tools wear detection and replacement technology. *The 3rd Shanghai International Tunneling Symposium Proceedings: Underground project construction and risk provision technology*: 152–157. Tongji University Publication Company.

He, R. & Wang, J.Y. Shanghai Yangtze River Tunnel synchronous construction method statement. *The 3rd Shanghai International Tunneling Symposium Proceedings: Underground project construction and risk provision technology*: 168–177. Tongji University Publication Company.

Sun, J. & Chen, X.K. 2007. Discussion of TBM selection for Shanghai Yangtze River Tunnel. *The 3rd Shanghai International Tunneling Symposium Proceedings: Underground project construction and risk provision technology*: 91–98. Tongji University Publication Company.

Yu, Y.M. & Tang, Z.H. 2007. Shanghai Yangtze River Tunnel construction survey technology. *The 3rd Shanghai International Tunneling Symposium Proceedings: Underground project construction and risk provision technology*: 158–167. Tongji University Publication Company.

Zhang, J.J. et al. 2007. Shanghai Yangtze River Tunnel TBM launching construction technology. *The 3rd Shanghai International Tunneling Symposium Proceedings: Underground project construction and risk provision technology*: 144–151. Tongji University Publication Company.