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Analysis on Engineering Characteristics of Underwater Shield Tunnel

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Abstract

In order to better guide the design and construction of underwater tunnel, this paper makes a detailed and in-depth study on the engineering characteristics of underwater shield tunnel by using the method of engineering example summary and geological generalization model. The research results show that the geological generalization model of underwater tunnel can be divided into the following categories: the tunnel is located in topsoil; the tunnel is located in the semi soil and semi rock composite stratum and the tunnel is located in the bedrock stratum.Underwater shield tunnel engineering is characterized by the coexistence of a single project and multiple stratum types, the diversification of shield construction methods and the manifestation of hydrodynamic pressure.

Keywords

Underwater; Shield Tunnel; Geological Generalization Model; Engineering Characteristics.

1. Introduction

Compared with the traditional mining method tunnel and urban subway shield tunnel, the underwater shield tunnel has been in a complex engineering geological environment for a long time [1], with the characteristics of infinite water supply. The stratum conditions of the underwater shield tunnel during the construction period are constantly changing from topsoil, semi soil and semi rock and full section rock stratum [2], and are disturbed by different types of shield machines, The external load acting on the lining changes constantly, which is difficult to be determined by classical theoretical design method [3]. For example, the field monitoring data of a section in the river crossing construction section of Nanjing Metro shows that [4], the measured external load on the tunnel top is about 81kpa less than the calculation result of Terzaghi relaxation earth pressure formula and about 226kpa less than the theoretical calculation result of soil column. In view of this, this paper makes a detailed and in-depth study on the engineering characteristics of underwater shield tunnel by using the method of engineering case summary and geological generalization model. The relevant research results not only provide reference for the design and construction of projects under similar conditions, but also have important significance for enriching and perfecting the design theory of segment lining structure of underwater shield tunnel.

2. Typical Engineering Statistics of Underwater Shield Tunnel

With the continuous maturity and improvement of shield construction method and equipment technology, it has been widely used in the construction of underwater tunnel, which provides technical support for solving the problems of crossing water system obstacles and connecting regional development. For example, the three world-famous underwater tunnel projects, the Anglo French

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channel tunnel, the danmesdorbel super channel tunnel and the Tokyo Bay Highway Tunnel in Japan, have been completed and put into operation. China has built many underwater tunnels in the Yangtze River, Yellow River, Songhua River, Qiantang River, Pearl River and other waters, and nearly 20 underwater tunnels crossing the Yangtze River and Huangpu River in Shanghai alone. According to the needs of urban development, many underwater shield tunnels have also been built in Wuhan and Nanjing. The more famous underwater shield tunnels are Wuhan Yangtze River Shield Tunnel Shanghai Chongming Island river crossing tunnel and Nanjing Yangtze River tunnel. The construction and development of underwater tunnel projects at home and abroad are in the ascendant. The incomplete statistical results of typical underwater shield tunnel projects at home and abroad are shown in Table 1.

Table 1. Typical engineering statistics of underwater shield tunnel

Serial number	Tunnel name	Tunnel type	Construction method	Overburden thickness	Water level conditions above overburden
1	Channel Tunnel	The outer diameter of the segment is 8.36m	Earth pressure shield	The maximum cover thickness is 90m and the minimum cover thickness is 21m	10m ~65m
2	Stobel super channel tunnel in Denmark	The outer diameter of the tunnel is 8.5m	Earth pressure shield	The maximum cover thickness is 90m and the minimum cover thickness is 21m	The average water depth is 65m
3	Tokyo Bay Highway Tunnel, Japan	The outer diameter of the tunnel is about 14m	Slurry shield	The maximum buried depth is 50m and the minimum overburden thickness is 11m	The maximum water depth is 40m
4	Shanghai Yangtze River Tunnel	The outer diameter of the tunnel is 15m	Slurry shield	The minimum cover thickness is 9m and the maximum cover thickness is 35m	The water depth is mostly 15m
5	Shanghai Jungong Road River Crossing Tunnel	The outer diameter of the tunnel is 14.5m	Slurry shield	The maximum overburden thickness is 28.2m and the minimum overburden thickness is 9.35m	The water depth of the main channel is 14 m ~ 16 m
6	Nanjing Weiqi road Yangtze River Tunnel	The outer diameter of the tunnel is 14.93m	Slurry shield	The overburden thickness of the river bottom section is about 10.79m, and the minimum overburden thickness is about 10.2m	The maximum buried depth of the tunnel is 60m
7	Nanjing Weisan Road River Crossing Tunnel	The outer diameter of the tunnel is 14.5m	Slurry shield	The maximum overburden thickness in the middle section of the river is 22m and the minimum overburden thickness is 9.8m	The maximum water depth is 62.3m
8	Wuhan Yangtze River Tunnel	The outer diameter of the tunnel is 11.37m	Slurry shield	The maximum soil cover thickness of the tunnel is 40.05m and the minimum soil cover thickness is 10.6m	The maximum water depth is about 30m
9	Wuhan Sanyang Road River Crossing Tunnel	The outer diameter of the tunnel is 15.2m	Composite slurry shield	The maximum overburden thickness in the middle section of the river is 29m and the minimum is about 11m	The maximum water depth is about 30m
10	Changsha Nanhu road crossing Xiangjiang tunnel	The outer diameter of the segment is 11.3m	Slurry shield	The minimum overburden thickness of the north line is 6.73m, the minimum overburden thickness of the south line is 7.89m, and the maximum overburden thickness of the section crossing the Xiangjiang River is 23.5m	The water depth is 17.8 ~ 21.3m

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11	Chongqing Main City Drainage River Crossing Tunnel	The outer diameter of the segment is 6.32m	Slurry shield	The overburden thickness of the tunnel is 21 ~ 33m, and the minimum overburden thickness of the middle section of the river is 8.5m	Maximum water depth 60m
12	Hangzhou Qiantang River Tunnel	The outer diameter of the tunnel is 11.3m	Slurry shield	The maximum buried depth of the tunnel is 23.1m and the minimum overburden thickness is about 10m	The water depth is generally 5m ~ 6.5m
13	Shiziyang Tunnel of Guangzhou Shenzhen Hong Kong	The outer diameter of the segment is 13.1m	Slurry shield	The maximum cover thickness is 26m and the minimum cover thickness is 8.7m	The maximum water depth is 26.6m
14	Yellow River Crossing Tunnel Project of Lanzhou Metro Line 1	The outer diameter of the tunnel is 6.48m	Composite slurry shield	The distance between the tunnel in the construction section and the riverbed floor is 9.8 ~ 35.3m	The water depth is generally 3 ~ 7m, and the maximum depth is 9m
15	Yellow River Crossing Project in the middle route of South-to-	The inner diameter of the segment is 7m	Slurry shield	The maximum buried depth of the tunnel is 23m and the minimum buried depth is 32m	The maximum groundwater level is 37m
16	Songhua River Harbin River Crossing Tunnel Project	The tunnel diameter is 6m	Gas pressurized slurry shield	The buried depth of the tunnel is about 10 ~ 18m	The maximum water depth in wet season is 16m
17	Foshan Dongguan Shiziyang Tunnel	Tunnel diameter 12m	Earth pressure shield	The thickness of soil covering on the top of the tunnel in the middle section of the Yangtze River is 70 ~ 90m	Maximum water depth 15m
18	Zhuji tunnel	Tunnel diameter 8.5m	Earth pressure shield	The overburden thickness of tunnel top under water is 35.8 ~ 55.3m	Water depth 5 ~ 8m

3. Study on Geological Generalization Model

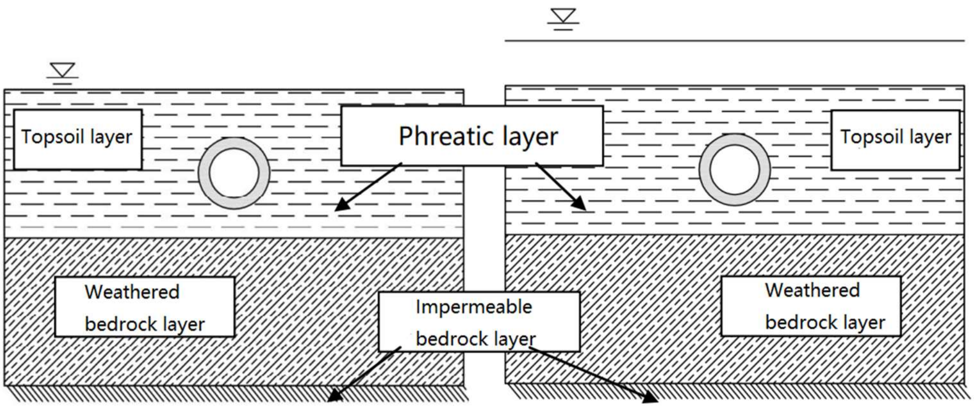
It is very important to determine the external load of segment lining in the design process of underwater shield tunnel. Constrained by the existing calculation level, it is impractical to establish a detailed geological calculation model, while the geological generalization model is closer to the actual situation of the project, which can reflect the influence of stratum conditions on the load bearing effect of excavation structure, and is widely used in the existing engineering calculation and research. Based on the statistics of typical underwater tunnel projects at home and abroad, the engineering characteristics of underwater shield tunnel are statistically summarized and analyzed from the mechanical characteristics, permeability characteristics, tunnel size, tunnel buried depth and construction method of tunnel stratum.

Based on the statistical analysis of 18 typical underwater shield tunnels at home and abroad, based on the stratum mechanical characteristics, permeability characteristics, tunnel location and other conditions, the stratum structure types of underwater shield tunnels can be divided into three types: the tunnel is located in the topsoil layer, the tunnel is located in the semi soil and semi rock layer and the tunnel is located in the weathered bedrock layer. The specific analysis is as follows:

(1) The tunnel is located in the topsoil

According to the mechanical characteristics and permeability of surface soil layer, it can be divided into clay layer and sand gravel layer. For the case that the tunnel is located in clay stratum, such as Shanghai Huangpu River crossing tunnel project, the shield tunnel is basically driven in sandy cohesive soil layer, and there is also sandy cohesive soil layer above the tunnel. For example, the surrounding rock stratum conditions of Tokyo Bay Highway Tunnel in Japan are soft alluvial clay, sand, proluvial clay and proluvial sandy soil, and the permeability coefficient of this kind of stratum is generally about 1 × 10-7cm / s, the distribution range of formation deformation parameters is large, and the compression modulus is generally about 2 ~ 20MPa; For the case that the tunnel is located in the sand gravel layer, such as the huangdungou tunnel section of Lanzhou Metro Line 1, the tunnel excavation and overlying stratum are gravel scouring stratum, which belongs to strong permeability stratum, and the permeability coefficient is generally about 1 × 10-2cm / s, with high formation sensitivity and large construction disturbance, and the compressive deformation modulus of the formation is generally 20 ~ 40MPa. According to the occurrence characteristics of groundwater, there is free water surface in the above two stratum structures, which is connected with the above surface. According to the definition of phreatic water, the aquifer under this kind of stratum is phreatic aquifer. In addition, there is generally a certain thickness of weathered bedrock below the topsoil layer, and a relatively complete bedrock is below the weathered bedrock. The permeability of the weathered bedrock stratum is located between the sand clay layer and the sand gravel layer, and its permeability coefficient is generally about 1 × 10-4cm / s, its deformation characteristics are relatively small, and the compression modulus is generally about 40MPa ~ 60MPa. When the groundwater level is high, the weathered bedrock stratum is the main aquifer, and the aquifer in the weathered bedrock provides the main water supply. To sum up, it can be seen that the tunnel is constructed in the topsoil, because the construction scope of underwater tunnel is underground

The water level is generally high, and there are generally weathered bedrock stratum conditions below the topsoil. When the topsoil has good permeability, the surrounding rock stratum of the tunnel presents the characteristics of phreatic aquifer; When the permeability of topsoil is poor, the tunnel will show the characteristics of construction above confined water. For example, during the construction in Guangzhou bank section of fo Guan Shiziyang Tunnel project, the tunnel is constructed in silt stratum, and the underlying stratum is weathered mudstone. The generalized geological model of the tunnel under the condition of topsoil is shown in Figure 1.

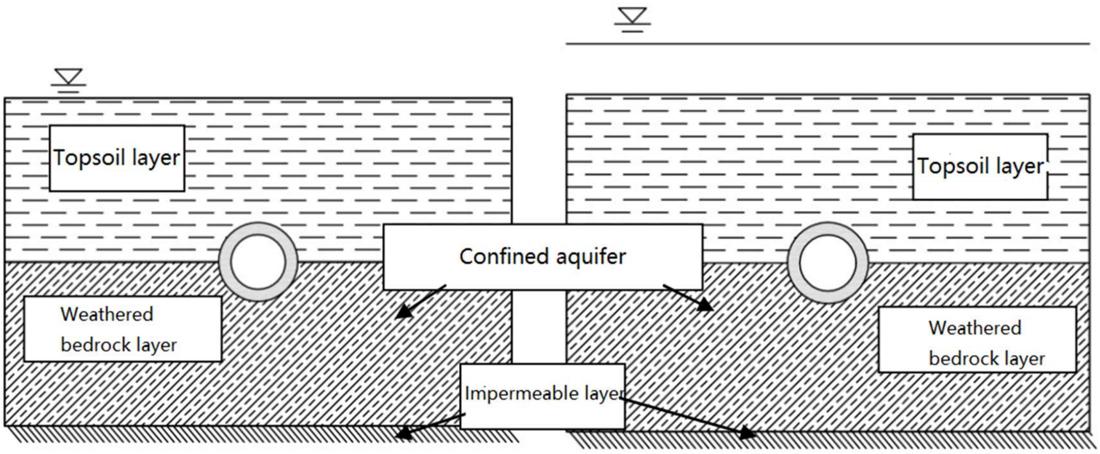


(a) The water level is at the surface (b) The water level is above the surface

Figure 1. Generalized geological model of tunnel in topsoil

(2) The tunnel is located in half soil and half rock stratum

Tunneling in semi soil and semi rock stratum is a common construction type of underwater shield tunnel, such as Nanjing Weiqi road and Weisan road river crossing shield tunnel, Changsha Nanhu road crossing Xiangjiang River Shield Tunnel, Chongqing main city drainage river crossing tunnel, Wuhan Yangtze River tunnel The river crossing sections of Wuhan Sanyang road river crossing tunnel, Guangzhou Shenzhen port Shiziyang Tunnel and other underwater tunnels have the construction phenomenon that the upper part is soil and the lower part is weathered bedrock. Among them, the river crossing section of Wuhan Yangtze River Tunnel cuts into the bedrock at a depth of 3.5m, and the river crossing tunnel of Wuhan Sanyang road cuts into the bedrock at a depth of about 1 / 2 of the diameter of the shield tunnel, The construction section in semi soil and semi rock stratum accounts for about 2 / 3 of the construction works of the whole river crossing section. The upper part of the stratum structure is generally soft clay or muddy clay layer with poor permeability, and the lower part is generally weathered bedrock layer with good permeability and large modulus. Under some stratum conditions, there will be sand gravel layer locally between soft clay and weathered bedrock layer. In terms of mechanical properties, the deformation modulus of soft clay and sand gravel layer is relatively large, while that of weathered bedrock layer is relatively small. Therefore, it can be seen that the surrounding rock of the tunnel is soft at the top and hard at the bottom; In terms of the permeability characteristics of the stratum, the permeability of the clay layer is poor, and the permeability of the sand gravel layer and weathered bedrock layer is relatively good. The sand gravel layer and weathered bedrock layer are the main aquifer, and the clay layer above the main aquifer is the relative water resisting layer, and the complete foundation rock below. According to the definition of confined water, the main aquifer is the confined aquifer. The generalized geological model of the tunnel in semi soil and semi rock stratum is shown in Figure 2.

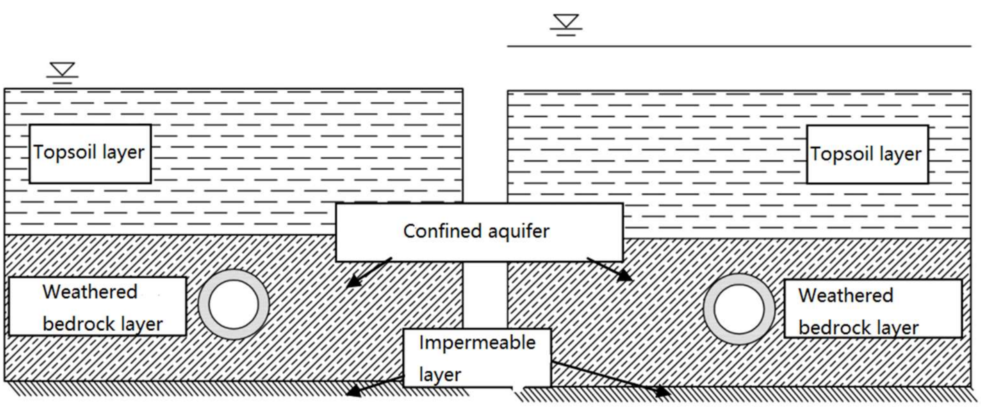


(a) The water level is at the surface (b) The water level is above the surface

Figure 2. The tunnel is located in the upper soft and lower hard composite stratum

(3) The tunnel is located in weathered bedrock stratum

When the tunnel crosses the water body, subject to the requirements of waterproof and drainage and the thickness of tunnel soil, the tunnel sections in some sections will be constructed in weathered bedrock strata, such as Shiziyang Tunnel of Guangzhou Shenzhen Hong Kong passenger line. The generalized model of tunnel stratum structure is shown in Figure 3.



(a) The water level is at the surface (b) The water level is above the surface

Figure 3. Generalized geological model of tunnel located in weathered bedrock stratum

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4. Engineering Characteristics of Underwater Shield Tunnel

(1) Multiple stratum types coexist in a single project

Underwater shield tunnels in different regions show different stratigraphic characteristics. For example, the Yangtze River Delta and Pearl River Delta obviously show the characteristics of soft soil and uneven soft and hard strata, while Changsha cross Xiangjiang tunnel mainly passes through hard bedrock strata. Compared with the three famous underwater shield tunnels in foreign countries, the underwater shield tunnels built in China show the characteristics of large diameter, shallow soil cover and high water pressure. In addition, China has a vast territory, numerous water systems and ever-changing stratum conditions, which constantly encounter new problems and challenges in engineering construction.

Due to the coexistence of multiple stratum types, when the tunnel is located in the underwater construction section, the construction conditions are extremely complex. Therefore, according to the unique characteristics of underwater shield tunnel built in China, targeted research should be carried out in order to better provide reference for the safe and rapid construction of underwater tunnel engineering under similar engineering geological conditions in China in the future.

(2) Diversification of shield construction methods

According to the analysis of the existing statistical results of underwater shield tunnel, slurry shield underwater tunnel construction is the current mainstream method. However, with the continuous improvement and improvement of earth pressure balance shield construction method, it has been gradually applied and recognized. Slurry shield and earth pressure shield have become the main construction methods of underwater shield tunnel construction. The disturbance effect of slurry shield construction on surrounding rock can be divided into four stages: ① the mud film on the tunnel face is gradually formed, and the mud water pressure balances the earth pressure and water pressure in front of the tunnel face through the mud film; ② The shield gradually enters and passes through the stratum, and the shield body exerts extrusion and friction on the surrounding rock. At the same time, there is a gap between the shield machine and the surrounding rock at the beginning of entering the stratum, that is, the surrounding rock will produce convergence deformation; ③ After the segment assembly is completed, the shield tail is gradually separated from the segment to form the shield tail gap. At the same time, affected by the synchronous grouting operation, the shield tail gap is continuously filled with slurry to prevent the stress release and deformation of surrounding rock; ④ The grouting slurry gradually hardens. With the progress of construction, the stratum behind the shield produces consolidation deformation and gradually tends to be stable. In this process, the mud water pressure at the tunnel face, the extrusion and friction generated by the shield and the convergence deformation of the surrounding rock, the convergence deformation and grouting pressure when the shield tail passes, the interaction between the segment structure and the surrounding rock after the shield passes, and the hardening deformation of the grouting body all have an important impact on the stress properties of the surrounding rock, Therefore, it will have an impact on the mechanical characteristics of segment lining structure. The disturbance effect of slurry shield construction on surrounding rock and structure can be divided into pre disturbance effect before shield arrival, disturbance effect during shield passing and disturbance and effect after shield passing.

The disturbance effect of the earth pressure shield construction process on the surrounding rock can also be divided into four stages: the earth pressure and disturbance effect in the earth bunker at the front face of the shield, the disturbance effect when the shield passes through, the disturbance effect when the shield tail passes through, the interaction between the segment lining and the surrounding rock after the shield passes through, and the influence of consolidation. Compared with the disturbance effect of slurry shield, the difference between the construction disturbance effect of earth pressure shield and slurry shield lies in the different support methods at the tunnel face. The earth pressure shield uses the earth pressure of the soil in the earth tank to balance the water pressure and earth pressure in front of the tunnel face. Therefore, the behavior of the soil in the earth tank will have

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an impact on the seepage field, stress field and deformation of the surrounding rock. The slurry shield is to balance the water pressure and earth pressure in front of the tunnel through the formation of mud film. In the process of action, the mud will penetrate into the soil and reinforce and improve the surrounding rock stratum. At the same time, the quality of the mud film will have an impact on the application of mud pressure and the seepage field around the rock. In addition, during the construction of slurry shield, the slurry in the slurry tank on the tunnel face will escape and enter the gap outside the shield shell through the notch position. The leaked slurry will have a certain impact on the seepage field and stress field of surrounding rock. Based on the above analysis, whether slurry shield construction or earth pressure shield construction will have different effects on the stress field, seepage field and deformation of tunnel surrounding rock, and then the shield tunnel construction method will have different effects on the stress of segment lining.

(3) The hydrodynamic pressure during construction is obvious

The existence of infinite water supply is an obvious feature of underwater tunnel construction. When the tunnel is excavated, the original equilibrium state of the seepage field in the surrounding rock of the tunnel is broken, and the groundwater begins to seep into the tunnel gradually. Shield tunnel construction has little impact on the disturbance of surrounding rock. In an ideal state, the sealing performance of tunnel face, shield body and structure connection is good, and groundwater cannot flow into the tunnel. However, in the actual construction process, the drainage conditions of the tunnel face and the connection between the shield and the structure are difficult to maintain in an ideal state. Only near the tunnel face, there is the phenomenon of groundwater infiltration with the slurry or the soil in the soil tank. In the environment of high water pressure, when groundwater infiltrates into the tunnel, it will have a drag force on the surrounding rock soil skeleton, that is, the phenomenon of hydrodynamic pressure, which will affect the stability of surrounding rock and the stress deformation of lining.

5. Conclusion

Based on the investigation of typical underwater tunnels at home and abroad, the engineering characteristics of underwater tunnels in China are summarized and analyzed. On this basis, the typical geological model of underwater tunnels is generalized and analyzed. The main conclusions are as follows:

1) The generalized model of underwater tunnel can be divided into three typical geological generalized models: the tunnel is located in topsoil, the tunnel is located in semi soil and semi rock composite stratum and the tunnel is located in bedrock stratum.

2) Underwater shield tunnel engineering is characterized by the coexistence of a single project and multiple stratum types, the diversification of shield construction methods and the manifestation of hydrodynamic pressure.

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