Design and Construction of the Qingdao Jiaozhouwan Subsea Tunnel

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1. Introduction

The Qingdao Jiaozhouwan subsea tunnel is the second subsea tunnel in China. The tunnel connects the two major parts of the Qingdao Metropolis, namely Qingdao city and the Huangdao district, and will play a crucial role in the regional development by a profound reduction in transportation time, see Figure 1. Qingdao lies in the southeast of Shandong province and is one of the largest industrial centers and port cities. It has some first-class harbors with international transportation links. In addition to the subsea tunnel there is a bay-crossing bridge under construction. Together with the existing around-bay highway there will be a total of three links between Qingdao and Huangdao.

![Figure 1. Location of the Qingdao Jiaozhouwan subsea tunnel.](image)

The 8.72 km long tunnel, of which 3.95 km is under sea, is located right at the mouth of the Jiaozhouwan bay. As shown in Figure 2 the tunnel consists of two tubes of the main tunnels and a service tunnel in between. The net distance between the main tunnel and the service tunnel is 16 m. The main tunnels have the horseshoe shape with a curved invert, and the service tunnel has straight walls and arch roof. Each main tunnel has three driving lanes with a total driving
width 10.75 m. In addition there are two side lanes and a maintenance lane (also served as emergency lane), making the total net width 13.5 m. The maximum net height of the main tunnel is 10.5 m. The pipes and cables for the municipal installations are laid in the space beneath the road surface and surrounded by back-filled materials. Other installations are shown in Figure 3. The maximum tunnel gradient is 3.9% of a length 830 m and the largest water depth along the tunnel route is 42 m. The minimum rock cover is 25 and 30 m respectively for the water depth less and larger than 20 m, which is relatively small in comparison to other subsea tunnels in the world. Three ventilation shafts are designed along the tunnel route and they are all located at the land sections. Drill and blast is used for tunnel excavation. More detailed general description of the tunnel can be found in reference [1].

![Figure 2. Layout and dimensions of the Qingdao subsea tunnel.](image)

![Figure 3. Cross section of the main tunnel.](image)
The designed average annual daily traffic (AADT) is 76,923 and the maximum driving speed is 80 km/h. The construction is scheduled to complete in 47 months and the tunnel is targeted to open for traffic in May 2011. The designed service period is 100 years. The estimated budget is CNY 3.8 billions equivalent approximately to USD 560 millions at the current exchange rate. At the time this paper is written more than 60% of the tunnel excavation is completed.

2. Geological and hydrogeological condition

An intensive site investigation program was conducted by all means available including land and marine borehole drilling and survey, land and marine seismic survey by reflection, other geophysical methods, borehole pumping and packer tests and laboratory tests. The rock types are mainly granite and volcanic rocks at the land and subsea section respectively. Bedrock is widely exposed and the top soil cover is very limited. The rock is basically hard and moderately jointed. A number of local faults and associated fracture zones were identified in the site investigation. The main type of the fault rocks are cataclasite and breccias, which are believed to provide water transport channels.

Rock mass classification was performed according to the Chinese system [2]: Class II-III 72.3%; Class IV 26.4% and Class V 1.3% (Class I is the best). Attempt was made in converting the class indexes to the internationally commonly used Q-system showing the Class II and III may correspond to Q-values ranging from 3 to 68 and mainly being fair to good quality. The wet uniaxial compressive strength ranges from 50 to 70 MPa. The permeability is generally low.

Figure 4 shows a sketch of the longitudinal geological section.

The actual geological conditions encountered during tunnel excavation have demonstrated the major geological structures have been revealed in the site investigation. As a matter of fact there is only one minor fault encountered so far, which was not detected in the site investigation.

3. Rock support design

For the main tunnels the rock support consists of two parts: the temporary support and the permanent support. The temporary support includes rock bolts and fiber-reinforced sprayed concrete. The bolts are galvanized for 0.4 mm to get the extensive corrosion protection. The sprayed concrete is normally C35 with synthetic fibers, high corrosion resistance and good water
tight characteristics. The length, diameter and spacing of the bolts and the thickness of the sprayed concrete are based on the rock mass classes. The permanent rock support is a completely closed circular lining of C50 cast-in-place reinforced concrete of 40-50 cm thick depending upon the rock quality. The structure design of the concrete lining considers 30% of the static water pressure. The standard rock support design for the main tunnels for each rock mass class is listed in Table 1. For the service tunnel the majority of sections of rock class II, III and IV the bolts and sprayed concrete are designed as the permanent support without concrete lining. A comprehensive study performed by SINTEF Rock Engineering, Norway, has demonstrated the feasibility of using bolting and shotcreting as the permanent rock support for tunnel sections of rock mass class II and III based on the Norwegian experience gained from more than 20 subsea tunnels in Norway [3]. The tunnel designer, namely the China Railway Tunnel Survey & Design Institute Co. Ltd, later proposed (1) to use the bolting and shotcreting as the permanent rock support for the service tunnel and (2) removing the concrete invert for the main tunnels. The first one was accepted and the second one was unfortunately rejected by an expert panel who evaluated the proposals.

Table 1. Summary of rock support for the main tunnels

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<thead>
<tr>
<th>Rock mass class</th>
<th>Temporary support</th>
<th>Permanent support</th>
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<tbody>
<tr>
<td>II</td>
<td>Local spot bolts φ22 L=3.0m C35, S8 synthetic fibers reinforced sprayed concrete 8-10 cm thick</td>
<td>C50/S12 cast-in-place concrete 400-500 mm</td>
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<tr>
<td>III</td>
<td>Roof φ22 bolts L=3.0m, 1.2x1.2 m Local φ8 steel-bar mesh C35, S8 synthetic fibers reinforced sprayed concrete 15 cm thick</td>
<td>C50/S12 cast-in-place concrete 450-500 mm</td>
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<tr>
<td>IV</td>
<td>Roof and walls φ22 bolts L=3.0m, 1.0x1.0 m φ8 steel-bar mesh 20x20 cm C35, S8 synthetic fibers reinforced sprayed concrete 20-25 cm thick Reinforced sprayed concrete rib, φ22 steel bar grid frame @1.0 m</td>
<td>C50/S12 cast-in-place reinforced concrete 500-700 mm</td>
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<tr>
<td>V</td>
<td>Roof φ76 self-advance anchor-bolt short pipe shed pre-installed prior to the excavation face, L=10-25 m, circumferential spacing 40 cm φ 42 spilling bolts L=3.0 m, circumferential spacing 40 cm Floor φ 42 spilling bolts L=7-10 m, circumferential spacing 40 cm φ8 steel-bar mesh 20x20 cm C35, S8 synthetic fibers reinforced sprayed concrete 30 cm thick Reinforced sprayed concrete rib, φ25 steel bar grid frame @0.5-0.7 m</td>
<td>C50/S12 cast-in-place reinforced concrete 600-700 mm</td>
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The principle for water control design is “mainly blocking and limiting the water inflow”. The designed allowable water inflow is 0.4 m$^3$/day per meter of tunnel length, and the major measure to control the water inflow is pre-grouting. Between the sprayed concrete and the concrete lining there is a layer of geotextile of 600 g/m$^2$ plus 2mm thick ECB waterproofing material. On the invert drainage plates are used. The leaked-in water will be collected by a system of pipes to an Ø500mm non-metallic pipe located beneath the road surface and finally transported to a sump, and then pumped out of the tunnel. There is one monitoring well every 50 m along the tunnel route.
4. Construction experience

With the understanding of water control being the key to successful construction, great attention has been paid to predicting the geological and hydrogeological conditions ahead of excavation face. Probe hole drilling is strictly enforced for the entire tunnel excavation. For each advance at least three holes are drilled, which is subjected to increase according to the jointing conditions. The length of the probe holes varies from 30 to 35 m with an overlapping of 8 m for two consecutive advances. The diameter of the probe holes is 90 mm. Rock cores are taken from the probe holes when necessary. In addition several geophysical methods are also used including TSP, georadar, infrared ray water detection and others.

Water flow from the probe holes is carefully measured and taken as the basis for judging if grouting is necessary. When the water inflow from a single hole exceeds 5 l/min grouting of the rock mass ahead of the tunnel face will be performed, which includes full face grouting, curtain grouting around the tunnel periphery and local spot grouting. This criterion is also used to control the quality of grouting from the control holes. Figure 5 illustrates the probe drilling and the full face grouting. Until now 29 major water leakages have been experienced and the maximum water inflow from a single 30 m long 100 mm diameter hole reached 160 l/min, see Figure 6. Observations from the construction sites indicated that the large water inflow was experienced not only in the fault and fracture/weakness zone but also in good rocks. Experience demonstrated the pre-grouting has been very successful. After excavation of the grouted section the tunnel was almost dry. Now the average water inflow per meter of tunnel length is 0.2 m³/day, equivalent to 139 l/min per km tunnel length, which is much lower than the commonly used the allowable value in Norway for the economical pumping that is 300 l/min per km tunnel length.

The reinforced sprayed concrete ribs are regularly used for the rock mass of class IV and V, which has been proved to be very effective. As shown in Figure 7 the reinforcement consists of φ22 steel bar grid frame @1.0 m spacing and φ25 steel bar grid frame @0.5-0.7 m spacing for class IV and V rock mass, respectively. The steel frame is installed after a 4 cm thick initial layer of sprayed concrete and will then be completely covered with sprayed concrete. The purposes of the sprayed concrete ribs are two fold: to increase the early strength and stiffness of the temporary support and to help the rock support prior to the excavation face. Figure 8 shows a photo taken close to the excavation surface with the sprayed concrete ribs installed. For crossing fault and fracture zones, in addition to the pre-grouting described above two other measures were taken. The first is the installation of spilling bolts ahead of excavation face and the other is the step excavation instead of the full face excavation for the standard tunnel sections.

Figure 5. Sketch for probe drilling and full face pre-grouting.
Figure 6. A photo showing the largest water flow from a single probe hole.

Figure 7. Structure of the reinforcement for the sprayed concrete rib.

5. Conclusions

The Norwegian experience in subsea tunneling has been successfully adopted in the Qingdao subsea tunnel, in particular the probe drilling and pre-grouting for water control. The water inflow rate after pre-grouting has reached a level much lower than the allowable rate commonly accepted in the Norwegian subsea tunneling practices. It has also been observed in a few sections of one main tunnel where the probe drilling and pre-grouting concept was not followed considerable water inflow was experienced, which had been treated by much more expensive
post-grouting, which again demonstrated the necessity of pre-grouting. The successful excavation and operation of the service tunnel will prove that the bolting and shotcreting can be used as the permanent rock support. There is no doubt that Qingdao subsea tunnel is a successful example of using the Norwegian subsea tunneling concept, although not completely.

It is believed the design and construction of rock support and water control in the Qingdao subsea tunnel is a breakthrough in China and will provide valuable experience for the further development in China’s subsea tunneling technology.

Figure 8. A picture showing the sprayed concrete ribs installed close to the excavation face.

6. References

